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EFFECT OF VIBRATION ON HEAT TRANSFER
FROM CYLINDERS IN FREE CONVECTION

THESIS

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EFFECT OF VIBRATION ON HEAT TRANSFER FROM CYLINDERS IN FREE CONVECTION

THESIS

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Preface

This report touches upon the subject of convective heat transfer. I hope that it will either establish a point of departure for further study or, more optimistically, provide some useful engineering design information. However, if neither of these purposes is served, I can truthfully say that this research has been of great personal value to me, for during the last six months I have become humbly reaware of my own inexperience and of the thrill of learning something new.

I wish to express my appreciation to Dr. Andrew J. Shine, Head, Department of Mechanical Engineering, Air Force Institute of Technology. As my thesis advisor, he gave timely suggestions and encouragement which were invaluable. Mr. Frank C. Jarvis, my laboratory technician, solved many practical problems involved with the assembly of equipment. In addition, he instructed me on the use of the Mach-Zender interferometer and provided vital assistance during the interferometer study. Finally, I wish to thank Mr. Millard W. Wolfe, Foreman, School Shops, Air Force Institute of Technology. Without his interest and patience this report would not have been completed on time.

David F. Neely

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List of Symbols

A	Lateral surface area of test cylinder - in^2
E	Voltage drop in heater and lead lines - volts
Gr	Grashof number - dimensionless
I	Current through circuit - amps
L	Length of test cylinder - in
Nu	Nusselt number - dimensionless
Pr	Prandtl number - dimensionless
Q_c	Convective heat loss - watts
Q_k	Conduction heat loss - watts
Q_l	Line loss - watts
Q_r	Radiation heat loss - watts
Q_t	Total power in circuit - watts
R	Resistance of lead wires - ohms
Re	Reynolds number - dimensionless
T_a	Temperature of ambient environment - F
T_f	Temperature of Boundary layer fluid - $(T_a + T_w)/2$ F
T_w	Temperature of cylinder surface - F
ΔT	Temperature difference - $(T_w - T_a)$ F
ΔT_o	Static Temperature difference - F
V	Vibration velocity - (4af) in/sec
a	Amplitude of vibration - in
d	Diameter of test cylinder - in
f	Frequency of vibration - cycles/sec

h	Heat transfer coefficient - BTU/hr ft^2 F
k_f	Thermal conductivity of air at T_f - BTU/hr ft F
v	Vibration intensity - (af) in/sec
ν_f	Kinematic viscosity of air at T_f - ft^2/sec

Abstract

The purpose of this investigation was to determine the effect of diameter, temperature difference, and vibration intensity on the free convective heat transfer rate from horizontal cylinders subjected to transverse vibrations in air.

The diameters of the cylinders used in this investigation were 0.085 and 0.25 inches. The cylinders were vibrated over a frequency range of 0 to 88 cycles per second and an amplitude range of 0 to 0.35 inches. The surface temperature of the cylinders ranged from 138 to 201 degrees Fahrenheit, and the maximum vibration intensity was 29 inches per second.

Above vibration intensities of 12 inches per second, the variation of the heat transfer rate for both cylinders followed the forced convection curve recommended by McAdams, and the value of the heat transfer rate was independent of the temperature difference. For a given temperature difference and vibration intensity, the value of the heat transfer rate increased as the cylinder diameter decreased. An interferometer study showed that the boundary layer was turbulent above vibration intensities of 12 inches per second.

EFFECT OF VIBRATION ON HEAT TRANSFER FROM CYLINDERS IN FREE CONVECTION

I. Introduction

Background

Free convection is actually conduction with subsequent fluid movement caused by changes in fluid density. Movement of the fluid takes place in a relatively narrow region known as the boundary layer. Most techniques designed to improve convective heat transfer have as their objective reducing the thickness of the boundary layer or increasing the transverse fluid motion in the boundary layer. Vibration is one method of increasing the heat transfer rate by additional fluid motion.

Purpose

The general purpose of this investigation was to determine the effect of diameter, temperature difference, and vibration intensity on the free convective heat transfer rate from the surface of horizontal cylinders subjected to transverse vibrations. A review of the literature indicated that a maximum vibration intensity (af) of 14.6 inches per second had been reported by Fand and Kaye (Ref 3:495). The specific objectives of this study were to increase the maximum vibration intensity and to correlate the results with the forced convection curve recommended by McAdams (Ref 6:259).

Scope

Two cylinders of different diameter and length were used in this investigation. The smaller cylinder was 0.085 inches in diameter and 10 inches long. The larger cylinder was 0.25 inches in diameter and 11 inches long. These cylinders were vibrated over a frequency range of 0 to 88 cycles per second and an amplitude range 0 to 0.35 inches. The vibration intensity (af) varied from 0 to 29 inches per second. Each cylinder was vibrated at static surface-to-air temperature differentials of 60, 90, 100, and 120 degrees Fahrenheit.

Approach

The cylinders were heated at rest on the vibration apparatus. Electrical power input to the cylinder heaters was varied until the desired static temperature differential was established. The cylinders were then vibrated with the heater power held constant. During vibration the surface temperature of the cylinders dropped, indicating an increase in the heat transfer rate. Data were collected, reduced, and plotted in graphical form.

Past Studies

A review of the literature revealed a number of studies over the past twenty years dealing specifically with the effect of vibration on the heat transfer rate from wires and small cylinders. Only the more recent and most applicable of these studies will be listed.

In 1955, Lemlich investigated the effects of horizontal and vertical transverse vibrations on the heat transfer rate from wires in free convection in air. The wires were 0.0253, 0.0396, and 0.081 inches in diameter and were vibrated over a frequency range of 39 to 122 cycles per second. The amplitude varied from 0 to 0.115 inches and the temperature difference varied from 7 to 365 degrees Fahrenheit. Lemlich reported an increase in the heat transfer coefficient of 400 percent and an independence of the heat transfer coefficient on the direction of vibration (Ref 5:1179).

In 1957, Shine studied the effect of transverse vibrations on the heat transfer rate from a vertical plate in free convection in air. The plate was vibrated over a frequency range of 11 to 315 cycles per second and a plate temperature range of 131 to 279 degrees Fahrenheit. The amplitude varied from 0 to 0.061 inches. Shine reported an increase in the heat transfer coefficient of 30 percent at a vibration intensity of 4.9 inches per second (Ref 8:56).

In 1961, Deaver et al. investigated the effects of vertical harmonic vibrations on the heat transfer rate from a 0.007 inch diameter wire in free convection in water. The frequency range was 0 to 4.25 cycles per second and the amplitude range was 0 to 1.38 inches. The maximum temperature difference was 140 degrees Fahrenheit. Deaver found regions of free, mixed, and forced convection and formulated empirical equations for each region. He also reported that at high vibration intensities the effect of vibration on the heat transfer rate agreed well with that of forced convection and that at low intensities the heat transfer rate was independent of the vibration intensity (Ref 1:254).

In 1961, James studied the effect of horizontal transverse vibrations on the heat transfer rate from cylinders in free convection in air. The frequency range was 107 to 167 cycles per second and the amplitude range was 0 to 0.064 inches. The temperature difference varied from 35 to 90 degrees Fahrenheit and the maximum vibration intensity was 7 inches per second. Cylinders of 0.085, 0.25, and 0.75 inches in diameter were used. James reported an increase in the heat transfer coefficient of 89 percent and found this increase to be dependent only on the vibration intensity (Ref 4:17).

In 1961, Fand and Kaye studied the effect of vertical transverse vibrations on the heat transfer rate from a 0.875 inch diameter cylinder in free convection in air. The frequency range was 54 to 225 cycles per second and the amplitude varied from 0 to 0.16 inches. The temperature difference varied from 25 to 185 degrees Fahrenheit and the maximum vibration intensity was 14.6 inches per second. Fand and Kaye reported that the effect of vibration on the heat transfer rate was negligible below intensities of 3.6 inches per second. They also found that for values of temperature difference less than approximately 100 degrees Fahrenheit and vibration intensities above 11 inches per second the heat transfer rate is independent of temperature difference and that for temperature differences above 100 degrees Fahrenheit the heat transfer rate can be obtained from an empirical equation (Ref 3:497).

In 1962, Shine and Jarvis studied the effect of vertical vibration on the heat transfer rate from cylinders in free convection in air. The cylinder diameters were 0.032 and 0.072 inches. The frequency range was 15 to 75 cycles per second and the amplitude range was 0.002 to 0.99 inches. Their report stated that the heat transfer rate is unaffected by vibration below intensities of 1 inch per second and that the variation of the heat transfer coefficient with vibration intensity appeared to parallel the forced convection curve recommended by McAdams (Ref 9:2).

In 1962, Russ studied the effect of horizontal transverse vibrations on the heat transfer rate from cylinders in free convection in air. The cylinder diameters were 0.065, 0.25, and 0.75 inches. The frequency varied from 0 to 130 cycles per second and the amplitude varied from 0 to 0.165 inches. The surface temperature of the cylinders varied from 125 to 167 degrees Fahrenheit and the maximum vibration intensity was 13 inches per second. Russ reported that the heat transfer rate for a given cylinder is dependent only upon the vibration intensity. He also found that the variation of the heat transfer rate as a function of vibration intensity was quite complex and that for the range of his investigation no simple analogy to that of forced convection existed (Ref 7:32).

Present Study

This study was an extension of the work of Russ. Vibration intensities of 29 inches per second were achieved through equipment redesign and modification. However, 30 data points were recorded in the low intensity region investigated by Russ. These points were compared to the results of Russ in order to establish the accuracy of the procedures and equipment used in this study. Correlation was excellent and the remaining data points were taken at vibration intensities in excess of 12 inches per second.

II. Experimental Equipment

The equipment used in this study can be divided into three main categories as listed below:

- Heat Transfer Apparatus
  - Test Cylinders
  - Power Control Equipment
  - Temperature Measuring Equipment
- Vibration Apparatus
  - Test Stand
  - Resonant Beam Assembly
  - Vibrator
  - Vibration Intensity Measuring Equipment
- Boundary Layer Study Apparatus
  - Mach-Zender Interferometer
  - Light Sources
  - Camera

Heat Transfer Apparatus

The 0.085 inch diameter cylinder was a 10 inch length of stainless steel tubing. The tube was heated electrically by attaching the power input leads directly to the ends of the cylinder so that the current passed through the cylinder itself. Four stainless steel support rods were soldered to the cylinder to prevent undesirable modes of vibration. A photograph of the cylinder is shown in Figure 2.

The 0.25 inch diameter cylinder was an 11 inch length of copper tubing. Heating was accomplished electrically by passing current through a single strand of 30 gage nichrome wire threaded axially through the cylinder. The power input lines were soldered to the ends of the wire and the entire heater was insulated electrically from the copper cylinder by a thin-walled cylindrical tube of alumina. Four stainless steel support rods were soldered to the cylinder to prevent undesirable modes of vibration. A photograph of the cylinder is shown in Figure 3.

The power control equipment consisted of two voltage regulators, two 3 ohm resistors, two ammeters, and a voltmeter. The two voltage regulators were Powerstat, type 140, and the voltmeter was a Ballantine, model 300. A single voltmeter was satisfactory for both cylinders since it had a variable scale. However, the 0.085 inch diameter cylinder required an ammeter with a range of 0 to 5 amperes and the 0.25 inch diameter cylinder required an ammeter with a range of 0 to 2 amperes. Both ammeters were Weston models. The voltage regulators were placed in series to obtain finer adjustments and the two 3 ohm resistors were added to stabilize the circuit by minimizing the effect of small variations in the contact resistance of the voltage regulators.

The ambient temperature was measured with a Parr calorimetric mercury-in-glass thermometer graduated to 0.05 degrees Fahrenheit. The cylinder surface temperature was measured with an iron-constantan thermocouple referenced to an ice-water bath and connected to a Rubicon potentiometer. The potentiometer was graduated to 0.005 millivolts or approximately 0.2 degrees Fahrenheit.

Vibration Apparatus

The test stand consisted of a steel frame with plywood sides and was completely filled with concrete. The top was a 0.5 inch thick steel plate welded to the frame. The base was 32 inches wide, 30 inches long, and the height of the test stand was 50 inches.

The resonant beam assembly consisted of two parallel beams 0.625 inches thick, 4 inches wide, and 40 inches long, and two movable spacers, each 4 inches long. The inner beam was made of steel and was connected to the vibrator. The outer beam was made of aluminum and contained the mounting bracket for the test cylinders. The position of the spacers determined the effective length of the beams, which in turn established the resonant frequency of the entire assembly. By varying the position of the spacers, a resonant frequency range of 80 to 315 cycles per second was obtained. A photograph of the resonant beam assembly is shown in Figure 5.

The vibrator was a Calidyne model 6 shaker with a frequency range of 0 to 700 cycles per second and an output force of 3.1 pounds per ampere of armature current. Although the maximum allowable armature current was 5 amperes, the equipment was operated at a maximum of 4 amperes to avoid failure of the vibrator or its power supply. This established a maximum force output of 12.4 pounds.

A General Radio type 631 strobotac was used to calibrate the frequency dial of the vibrator power supply. The strobotac had a frequency range of 10 to 240 cycles per second. A Gaertner Scientific Corporation telemicroscope was used to measure the amplitude of vibration. This instrument was graduated to 0.0001 inches.

Boundary Layer Study Apparatus

The Mach-Zender interferometer used in this study had optical parts 6 inches in diameter and a test section 19 inches long. The interferometer was suspended by coil springs attached to a steel frame. The frame was mounted on wheels and could be raised or lowered by means of a hydraulic jack. A photograph of the interferometer is shown in Figure 6.

Three light sources were used in this study. A mercury lamp was used for coarse fringe adjustments, a zirconium lamp for fine fringe adjustments, and a spark lamp for obtaining the interferograms. A Graflex camera, employing type 44 polaroid film, was used for the interferograms.

III. Measurements

The acquisition of raw data required the measurement of six experimental variables. These variables were the ambient air temperature, cylinder surface temperature, frequency of vibration, amplitude of vibration, current, and voltage. The measurement of each of these variables will be discussed separately in the following paragraphs.

Temperature

The ambient air temperature was measured with a mercury-in-glass thermometer graduated to 0.05 degrees Fahrenheit. The physical location of the thermometer was most important since vertical and horizontal temperature gradients as high as 2 degrees Fahrenheit per foot existed within the laboratory. Consequently, the thermometer bulb was placed at the same vertical level of the test cylinder and within 6 inches of the cylinder horizontally.

The temperature of each cylinder was measured with an iron-constantan thermocouple soldered to the cylinder surface. The location of this thermocouple was critical since each cylinder had a temperature variation along its length caused by heat conduction along the support rods. Consequently, nine thermocouples were soldered to the surface of each cylinder and the temperature recorded at each location during four static runs and four vibration runs. These temperatures were plotted, the area under each curve determined, and the average temperature obtained by dividing the area by the length of the cylinder. The average temperature always occurred at the same location on each cylinder. It was at this location that the cylinder surface temperature was measured for all subsequent test runs.

The effect of random air motion in the test area on the cylinder surface temperature was negligible. This was determined during five test runs in which the cylinder was completely enclosed within an air shield. The cylinder was then heated and vibrated at intensities in excess of 12 inches per second. When the cylinder surface temperature had stabilized, its value was recorded and the air shield removed. After five minutes, the surface temperature was again recorded. During all runs, the temperature did not change after the shield was removed.

Vibration Intensity

The frequency of vibration was set by a dial on the vibrator power supply. The dial reading was checked periodically with a strobotac and found to agree within 2 cycles per second. The amplitude of vibration was obtained by focusing the telemicroscope on a narrow width of reflecting tape placed on the end of the support cylinder. When the cylinder was vibrating, this width of tape became a continuous, distinct band. The width of this band was measured with the telemicroscope. This measurement was then corrected for the width of the tape and became equal to double the amplitude of vibration.

Power

The current to the heater element of each cylinder was measured with a conventional ammeter. Before each run at one of the four static temperature differentials, the ammeter was compared to another ammeter of the same type. The maximum difference in the two readings was 0.01 amperes. Voltage was measured with an electronic voltmeter. However, the voltage drop in the heater element of each cylinder was not measured directly. It was necessary to connect the voltmeter in such a way that a line loss was also included in the instrument reading. Consequently, the total power input had to be corrected for this line loss in order to obtain the power delivered to the heater element.

IV. Calculation of Losses

The heat lost by convection from the cylinder surface was determined by subtracting the line, radiation, and conduction losses from the total power in the circuit. End losses were considered negligible for both cylinders. This assumption was based on a comparison of lateral surface area to end surface area. The calculation of the line, radiation, and conduction losses will be discussed in the following paragraphs.

Line Losses

The line losses were computed from the line current and resistance. The line current was measured and the line resistance was calculated by measuring the voltage drop in one foot of wire at different values of current. The total resistance of the lead wires for the 0.085 inch diameter cylinder was variable and is plotted against current in the wire in Figure 7. However, the total resistance of the lead wires for the 0.25 inch diameter cylinder remained constant at a value of 0.167 ohms. This is due to the fact that the maximum current required by the 0.25 inch diameter cylinder was only 1.38 amperes as compared to a maximum current of 5.1 amperes for the 0.085 inch diameter cylinder.

Radiation and Conduction Losses

In this investigation, the radiation and conduction losses were computed indirectly. Based on the assumption that the heat lost by radiation and conduction was independent of the vibration intensity and only a function of the temperature difference, the following procedure was used in the calculation of these losses:

1. Each cylinder was heated, at rest, to different values of static temperature difference.

2. For each value of static temperature difference, properties of the fluid in the boundary layer were computed at the arithmetic average of the cylinder and ambient temperatures.

3. With the fluid properties, cylinder diameter, and temperature difference established, the product of the Grashof and Prandtl numbers are computed.

4. With the Grashof-Prandtl product known, the Nusselt number was obtained from McAdam's free convection curve (Ref 6:176).

5. The convective heat transfer rate from the cylinder surface was determined using this Nusselt number.

6. The sum of the radiation and conduction losses was computed by subtracting the line and convective losses from the total power in the circuit.

7. The sum of the radiation and conduction losses was then plotted against temperature difference for each cylinder. These graphs are shown in Figures 8 and 9.

V. Experimental Procedure

Four vibration tests were conducted on each cylinder. Each test consisted of five to fifteen runs or data points with the cylinder heater power held constant. Although the heater power was constant for a given test, it had a different value for each test. These values corresponded to static cylinder-to-ambient temperature differentials of 60, 90, 100, and 120 degrees Fahrenheit.

The specific experimental procedure used in each vibration test consisted of the following steps:

1. The cylinders were heated, at rest, to a specific value of static temperature difference.

2. When the desired static temperature difference was established, the power input to the cylinder heaters was held constant and the cylinders were vibrated at various intensities.

3. When the cylinder surface temperature stabilized at each vibration intensity, raw data were recorded.

VI. Calculation of Parameters

The heat transfer rate from the cylinder surface was calculated by subtracting the line, radiation, and conduction losses from the total power in the circuit. The total power was determined from the recorded current and voltage. The line loss was determined from the recorded current and line resistance. The sum of the radiation and conduction losses was determined from the graphs shown in Figures 8 and 9 and discussed earlier. The vibration intensity was determined from the product of the amplitude and frequency of vibration.

The Nusselt number was calculated from

$$Nu = (h)(d/k_f) = (3.412Q_c/A\,\Delta T)(d/k_f) \qquad (1)$$

For the 0.085 inch diameter cylinder, 10 inches in length, Eq (1) reduced to

$$Nu = 1.305Q_c/k_f\,\Delta T$$

For the 0.25 inch diameter cylinder, 11 inches in length, Eq (1) reduced to

$$Nu = 1.184Q_c/k_f\,\Delta T$$

The Reynolds number was calculated from

$$Re = Vd/\nu_f = 4afd/144\nu_f \tag{2}$$

For the 0.085 inch diameter cylinder, Eq (2) reduced to

$$Re = 2af/84.7\nu_f$$

For the 0.25 inch diameter cylinder, Eq (2) reduced to

$$Re = 2af/288\nu_f$$

VII. Analysis of Errors

Human and instrument errors could have been introduced into the raw data during the measurement of any one of the six fundamental variables. An analysis of the individual and overall errors is presented in this section.

Power Measurement

The ammeters used in this study had a maximum error of 0.75 percent of the full scale reading. The minimum reading during test runs was 3.31 and 0.91 amperes for the smaller and larger cylinder, respectively. These values yield maximum errors of 2.27 and 1.65 percent.

The electronic voltmeter used in this study had an accuracy of 2 percent of the full scale reading. The 0.085 inch diameter cylinder required a full scale reading of 1 volt, and the 0.25 inch diameter cylinder required a full scale reading of 10 volts. The maximum error becomes 2.86 percent for the smaller cylinder and 5.4 percent for the larger cylinder.

Vibration Intensity

The frequency of vibration was obtained from a dial on the vibrator power supply. The minimum frequencies of vibration were 77 and 80 cycles per second for the smaller and larger cylinders, respectively. Based on these figures, the maximum error would be 2.6 percent for the 0.085 inch diameter cylinder and 2.5 percent for the 0.25 inch diameter cylinder.

The amplitude of vibration was recorded as the average of two readings. The maximum deviation from the average was 0.005 inches. Based on an amplitude of 0.25 inches, a representative error of 2 percent was calculated.

Temperature

Measurement of the ambient temperature and the cylinder surface temperature could have introduced relatively large errors into the calculation of parameters. Although actual values of these two temperatures were not used directly in the calculation procedure, their difference established the numerical value of ΔT At high vibration intensities, values of ΔT less than 10 degrees Fahrenheit were not uncommon. Consequently, an instrument error of 1 degree Fahrenheit could cause a relatively large error of more than 10 percent. In addition, the presence of the thermocouple on the cylinder surface tended to disturb the boundary layer fluid, and even if there were no instrument error this disturbing effect may result in incorrect temperature measurements (Ref 6:19[illegible]).

Overall Error

The expressions for the maximum overall error in the calculation of the Nusselt number and Reynolds number were obtained by writing the equation for these parameters in finite difference form as

$$\Delta Nu = C/k_f \left[\frac{\Delta Q_c}{(T_w - T_a)} + \frac{Q_c \, \Delta (T_w - T_a)}{(T_w - T_a)^2} \right] \qquad (3)$$

and

$$\Delta Re = \frac{f \, \Delta 2a + 2a \, \Delta f}{C_1 \quad \nu_f} \qquad (4)$$

where C and C_1 are constants determined by the length and diameter of the cylinder. Errors in k_f and ν_f were taken as zero since values of these properties varied only slightly over the temperature range of this investigation. The error in ΔT could not be accurately determined. However, a value of 0.5 degrees Fahrenheit was assumed. The expression for the maximum error in convective heat transfer is derived in Appendix B. Applying Eqs (3) and (4) to run number 19 on the 0.25 inch diameter cylinder, the maximum overall error was calculated to be 2.66 for the Nusselt number and 38.3 for the Reynolds number. These values correspond to errors of 14.9 and 4.3 percent, respectively.

VIII. Results and Correlation

The results of this investigation are presented in both tabular and graphical form. Tables III and IV contain listed values of the measured variables and calculated parameters for all of the tests. Values of the calculated parameters shown in Tables III and IV are also presented graphically in Figures 10 through 14. A discussion of each graph is contained in the following paragraphs. In addition, overall correlation with other authors is presented and an analysis of the interferograms is included at the end of the section.

Variation of the Heat Transfer Coefficient With Vibration Intensity

Figures 10 and 11 show, in non-dimensional form, the variation of the heat transfer coefficient with vibration intensity for each cylinder. The vibration intensity was varied from 0 to 12 inches per second and the static temperature differential was 90 degrees Fahrenheit. The purpose of these graphs was to compare the results of this study with those of Russ and thereby establish the validity of the experimental procedures employed by this author. Correlation with Russ was limited to the low intensity region since he had not obtained vibration intensities above 13.0 inches per second. As shown in Figure 10, correlation of results for the 0.085 inch diameter cylinder was excellent. The difference between the two curves is never more than 2 percent and the static value of each curve is within 1 percent of the free convection value as found in McAdams (Ref 6:176). As shown in Figure 11, correlation of results for the 0.25 inch diameter cylinder is satisfactory. In general, the two curves differ by about 10 percent. This difference could be explained by pointing out that the static value of the heat transfer coefficient as computed by Russ differs from McAdams by 10 percent, while the static value determined in this report agrees with McAdams to within 1 percent. It is reasonable to assume that this deviation could be present in each of the data points reported by Russ and thus explain the lack of better correlation.

Figures 12 and 13 show, in non-dimensional form. the variation of the heat transfer coefficient with vibration intensity at intensities from 12 to 29 inches per second and with static temperature differentials of 60, 90, 100, and 120 degrees Fahrenheit. These graphs show clearly that at vibration intensities above 12 inches per second the variation of the heat transfer coefficient for both cylinders follows the forced convection curve found in McAdams (Ref 6:259) and, for a given cylinder diameter and vibration intensity, its value is independent of the temperature difference. A study of the graphs also reveals that, for a given vibration intensity and temperature difference, the value of the heat transfer coefficient increases as the cylinder diameter decreases.

Correlation With Other Authors

Correlation with the results of Shine and Jarvis, Fand and Kaye, Deaver, and Russ is shown in Figure 14. As discussed earlier, agreement with Russ is good. Correlation with each of the other authors will be discussed separately in the following paragraphs.

Agreement with the results of Shine and Jarvis is not satisfactory. Although the slopes of both curves are identical at high Reynolds numbers, the numerical values of the heat transfer coefficient for the same Reynolds number differ by about 25 percent. In an effort to find an explanation for this difference, this author examined closely the experimental data and computations of Shine and Jarvis but was unable to find an explanation for the lack of agreement.

To facilitate comparison with the work of Fand and Kaye, their results were extrapolated to vibration intensities of 16 inches per second. Correlation with these extrapolated results is excellent. Both curves follow the forced convection curve of McAdams, and values of the heat transfer coefficient for the same Reynolds number differ by only 12 percent. This difference could be explained by pointing out that Fand and Kaye used an internal thermocouple to measure cylinder surface temperature while an external thermocouple was used in this study.

Correlation with the results of Deaver is excellent at high vibration intensities. However, in the region near the critical vibration intensity below which heat transfer is unaffected, the slopes of the two curves are different. The results of Deaver show a smooth transition from subcritical to above critical intensities, while the results of this study show a rather abrupt increase in heat transfer as the critical intensity is reached. The difference in the two curves could be due to the fact that Deaver conducted his investigation with water as the ambient fluid. The dimensions of the tank holding the water were not much larger than those of the test cylinder. Consequently, with amplitudes as high as 2.76 inches, the possibility of disturbances in the ambient fluid must be considered.

Analysis of the Interferograms

Interferograms of the 0.25 inch diameter cylinder at various vibration intensities are shown in Figures 15 and 16. Although a quantitative analysis of the boundary layer is impossible, some qualitative information can be obtained from the interferograms. It is seen that complete transition to turbulent flow has taken place. and that the boundary layer is stretching to enclose the region of motion of the cylinder. In addition, the boundary layer has become quite thin and is similar to that found in forced convection.

IX. Conclusions and Recommendations

The results of this investigation of the free convection heat transfer from vibrating cylinders lead to the following conclusions:

1. The variation of the heat transfer coefficient for vibration intensities between 12 and 29 inches per second follows the forced convection curve recommended by McAdams and the slope of the curve is independent of the cylinder diameter.

2. For a given cylinder diameter and vibration intensity, the value of the heat transfer coefficient is independent of the temperature difference for vibration intensities between 12 and 29 inches per second and within the range of temperature difference used in this investigation.

3. The results of this investigation are in excellent agreement with the results of Russ and Fand and Kaye.

4. The boundary layer is turbulent for vibration intensities between 12 and 29 inches per second.

Based on the assumption that this report will provide a starting point for further study, the following recommendations are made:

1. That the effect of direction of vibration on the heat transfer coefficient be determined.

2. That cylinders of high relative value of thermal diffusivity be used to minimize temperature stabilization time.

3. That internal thermocouples be used to minimize errors in temperature measurement.

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APPENDIX A

Figures

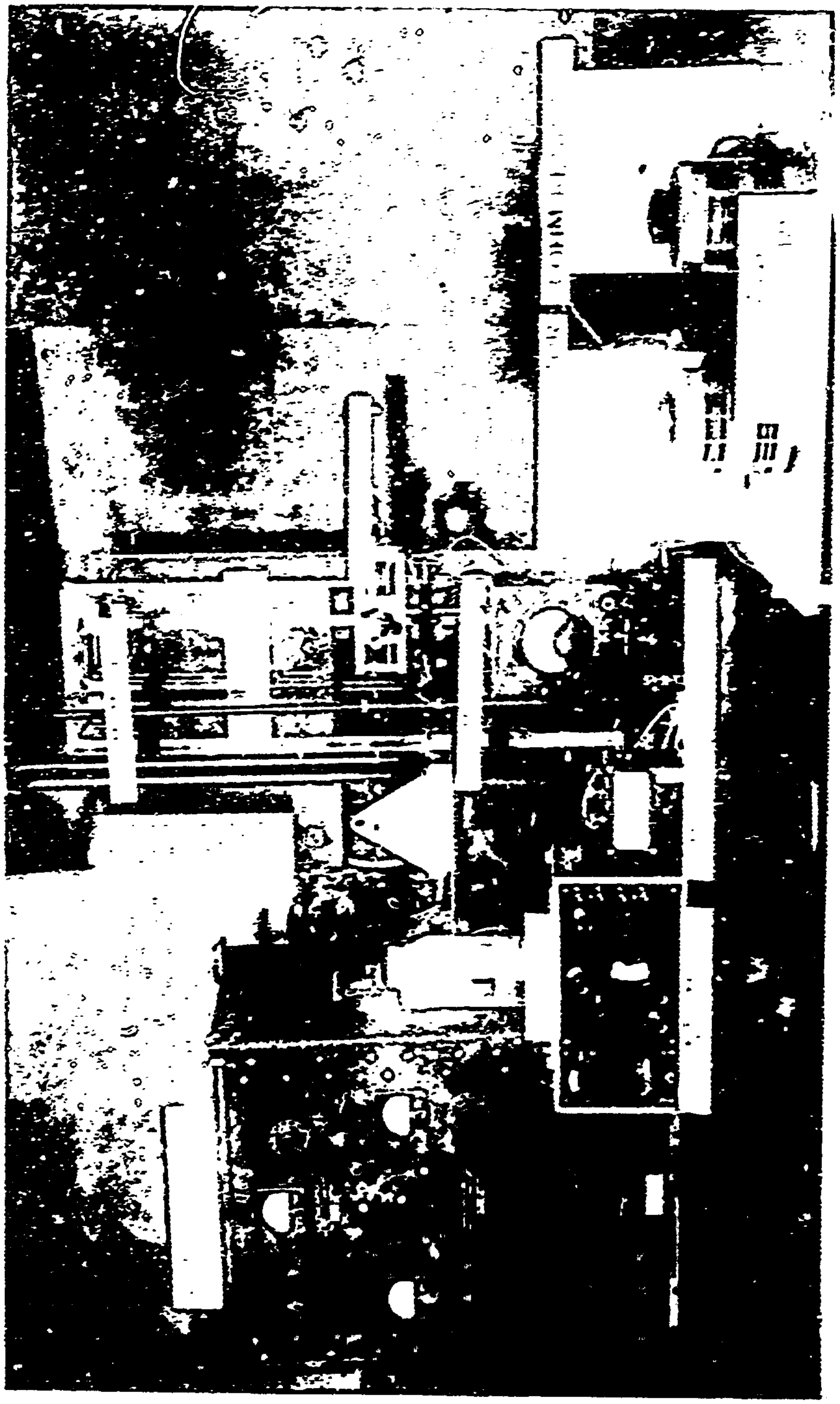


Figure 1
Photograph of the Test Apparatus

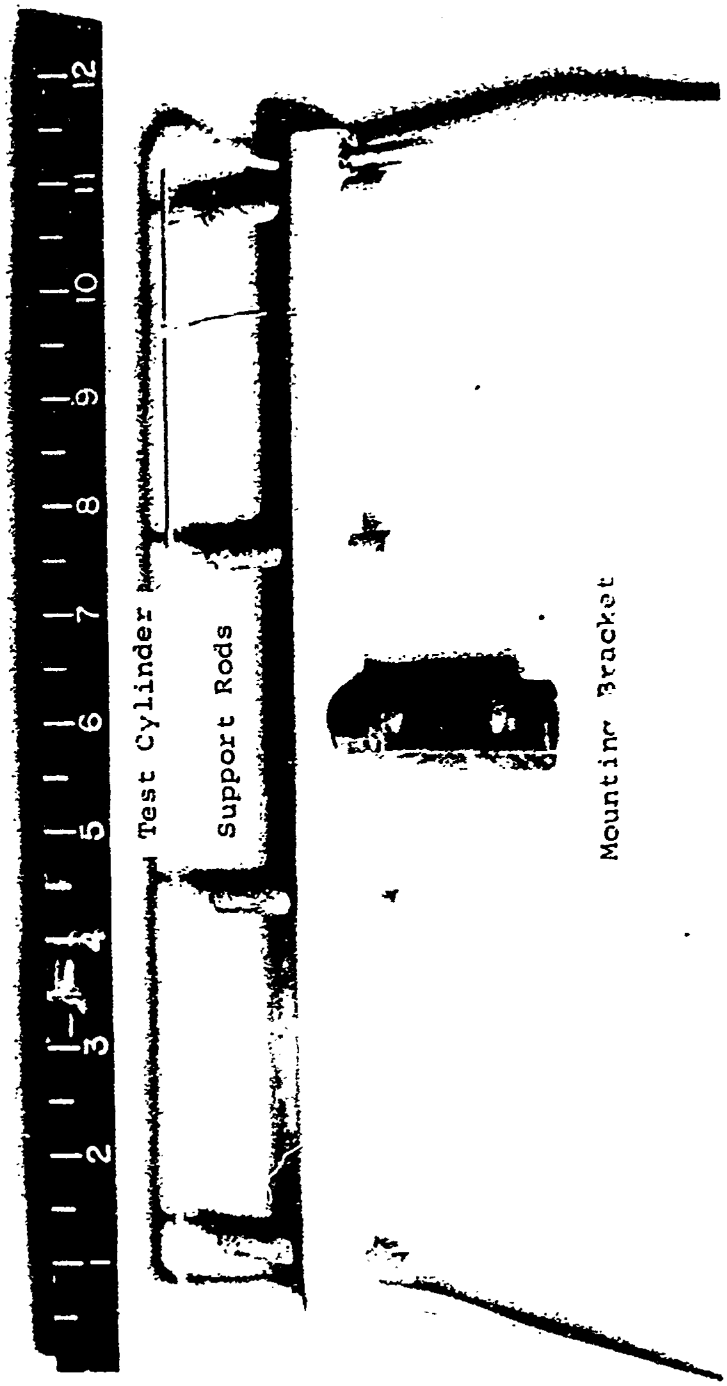


Figure 2
Photograph of the 0.085 Inch Diameter Test Cylinder

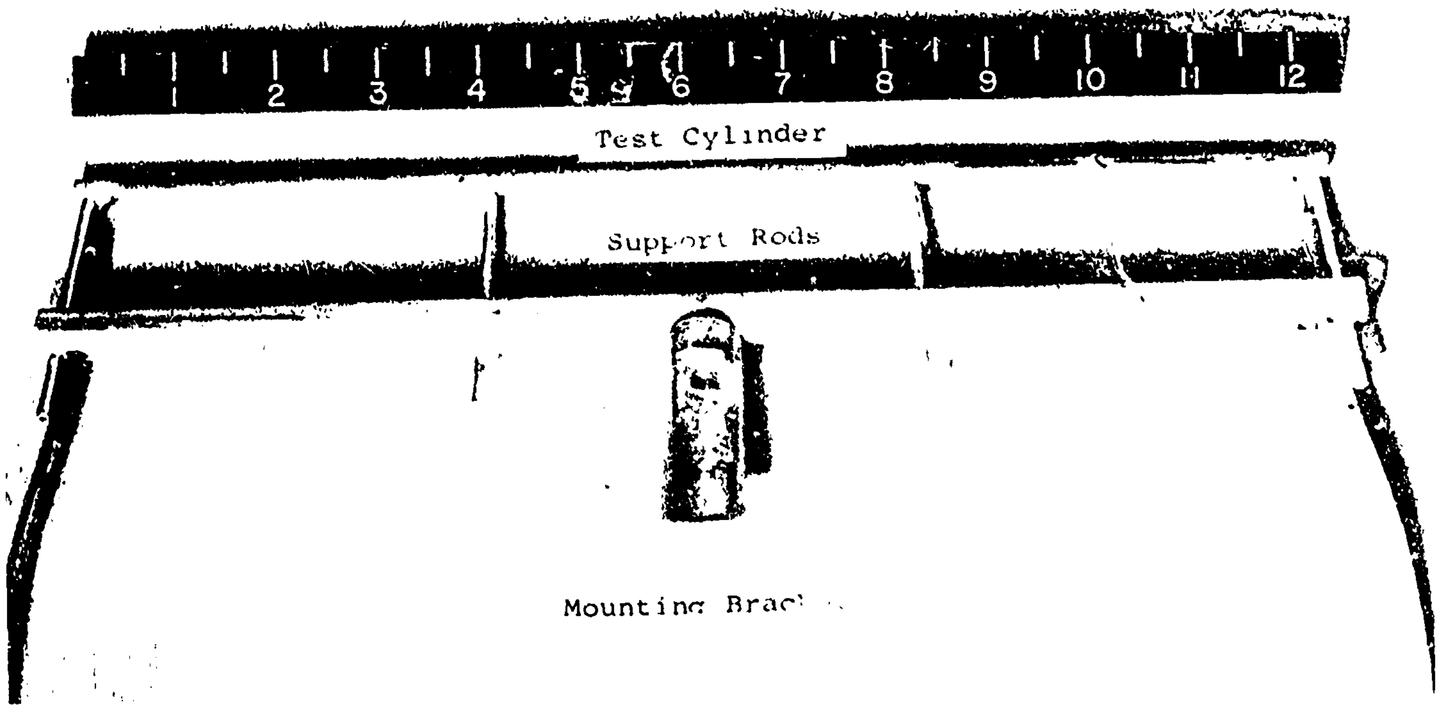


Figure 3
Photograph of the 0.25 Inch Diameter Test Cylinder

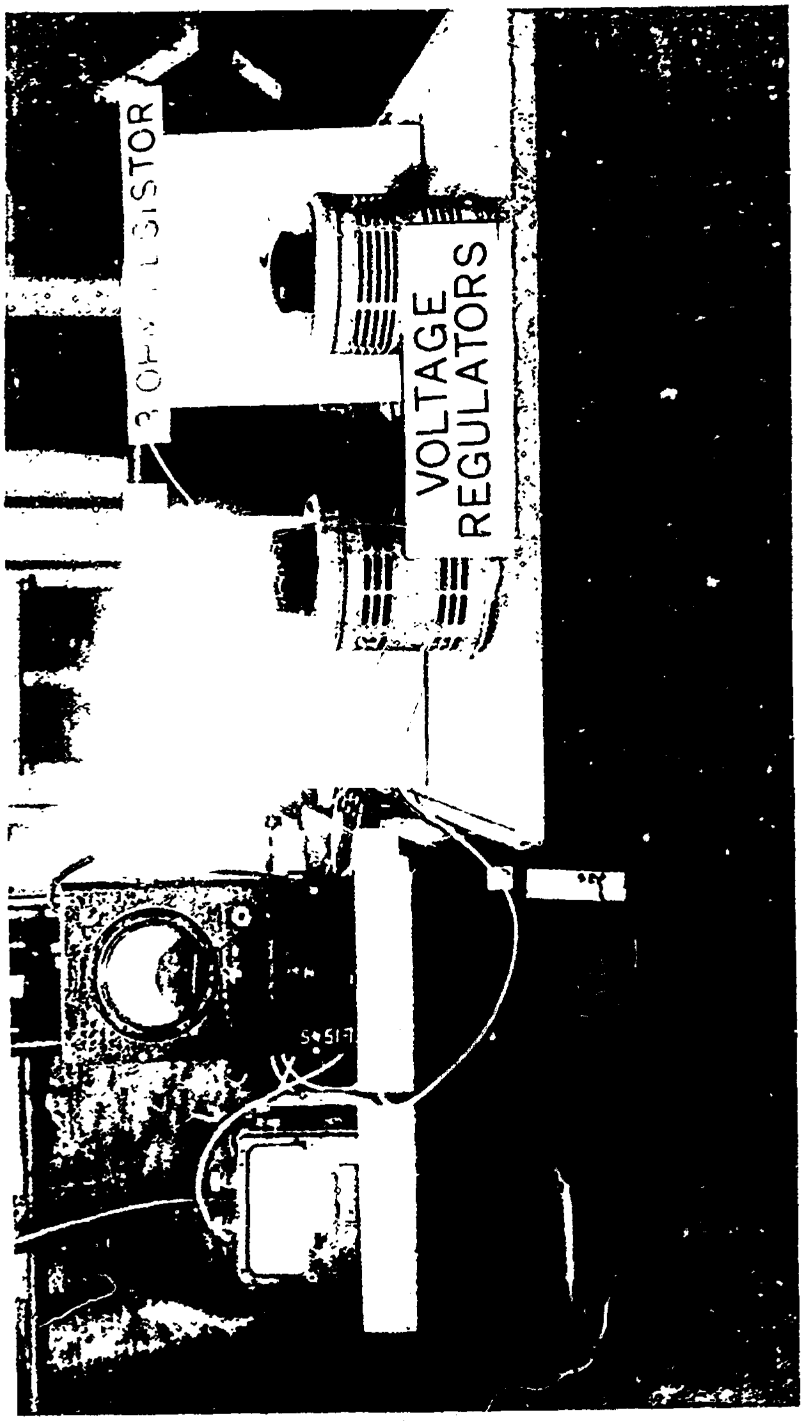


Figure 4
Photograph of the Power Control Equipment

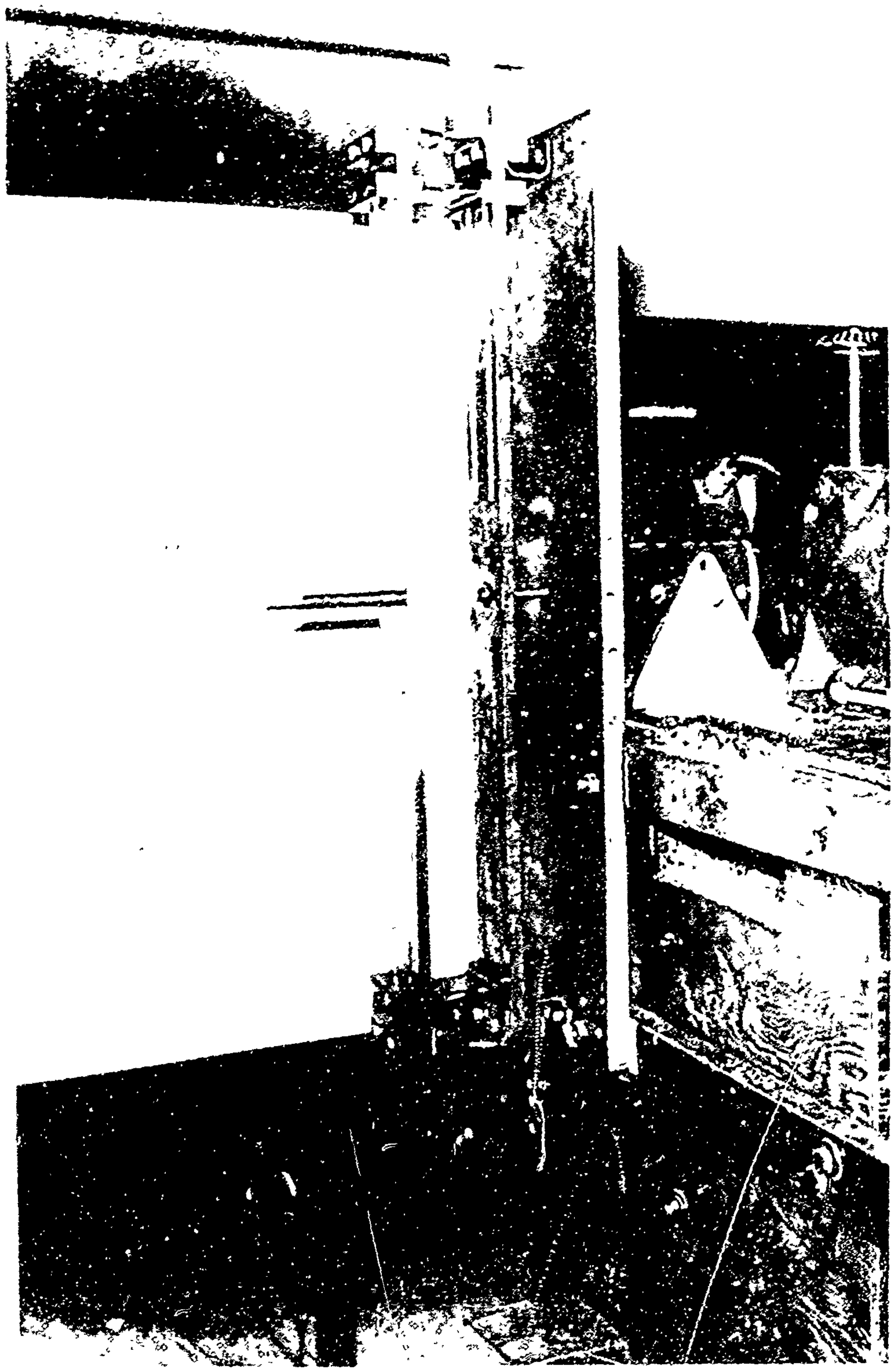


Figure 5
Photograph of the Resonant Beam Assembly

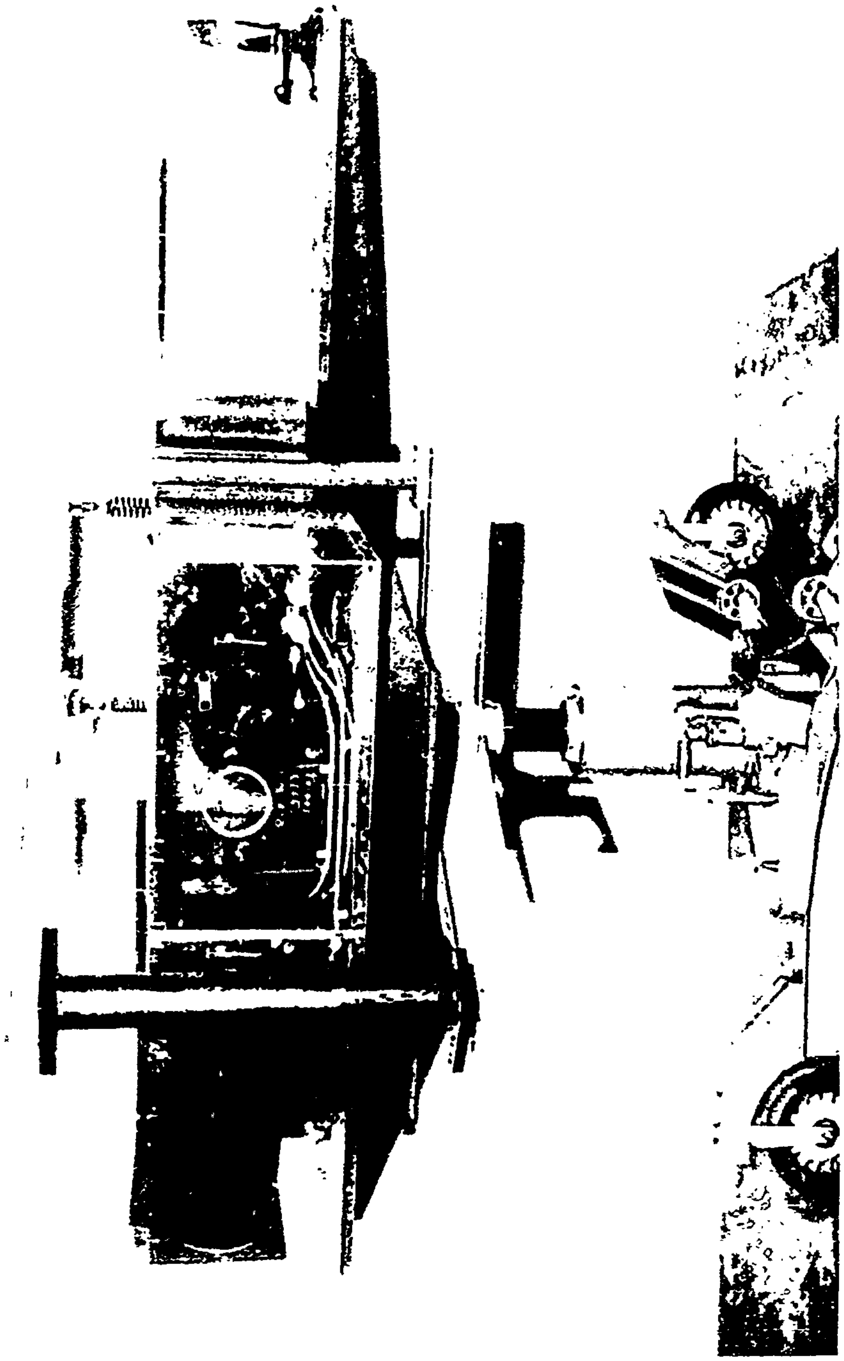


Figure 6
Photograph of the Interferometer

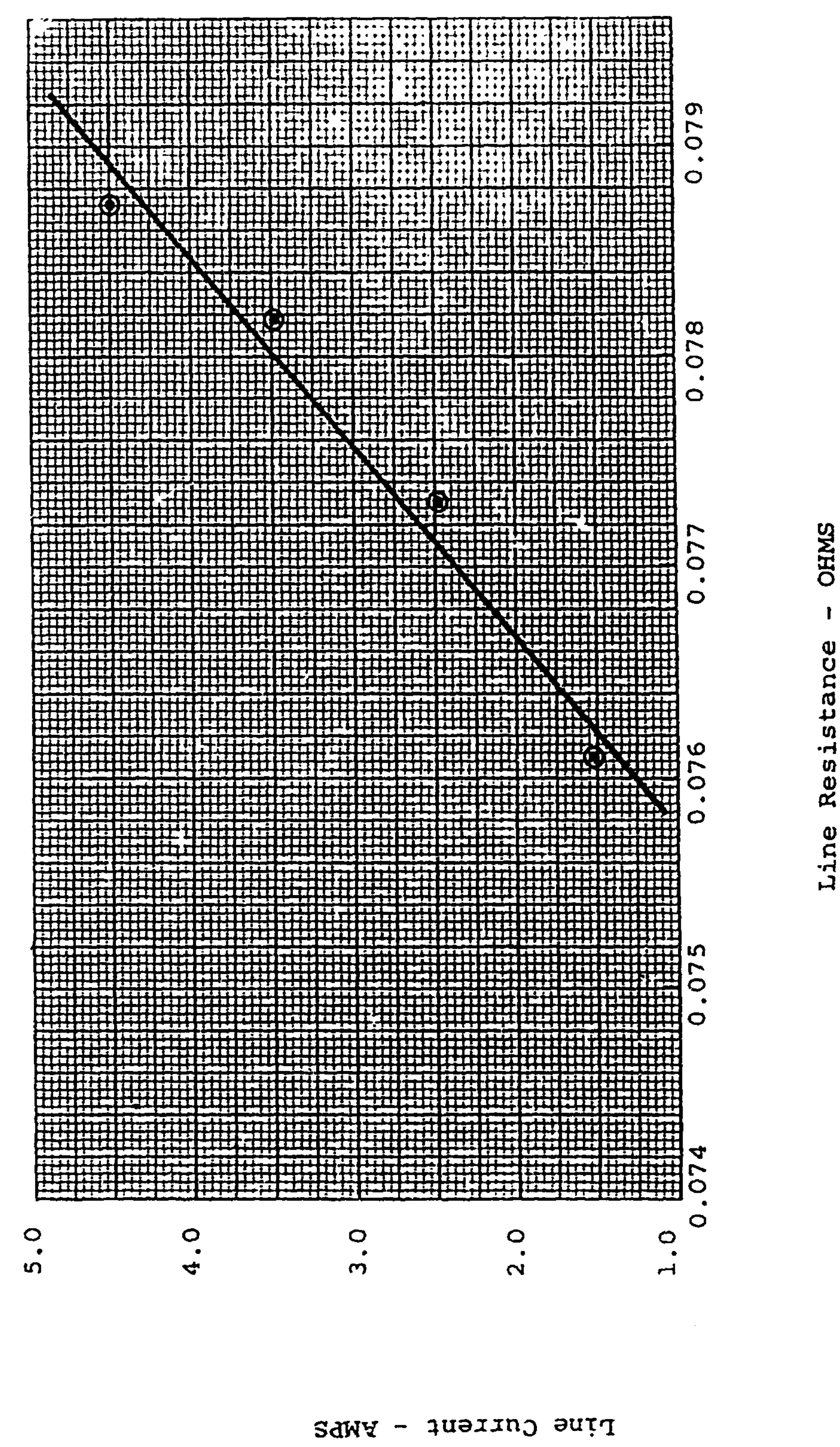


Figure 7
Variation of Line Resistance With
Current for the 0.085 Inch Diameter Test Cylinder

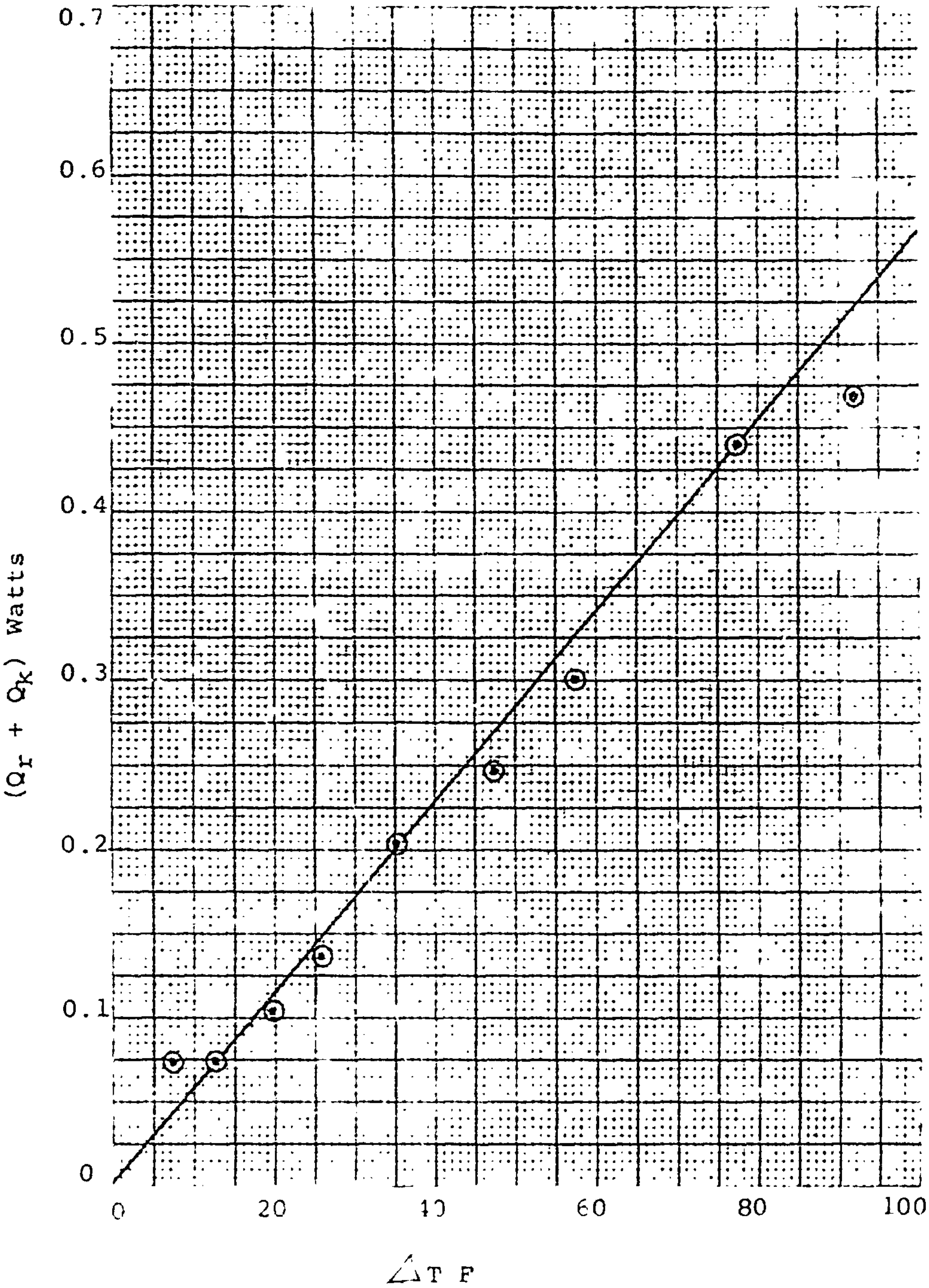


Figure 8
Variation of Radiation and Conduction Losses With Temperature Difference for the 0.085 Inch Diameter Test Cylinder

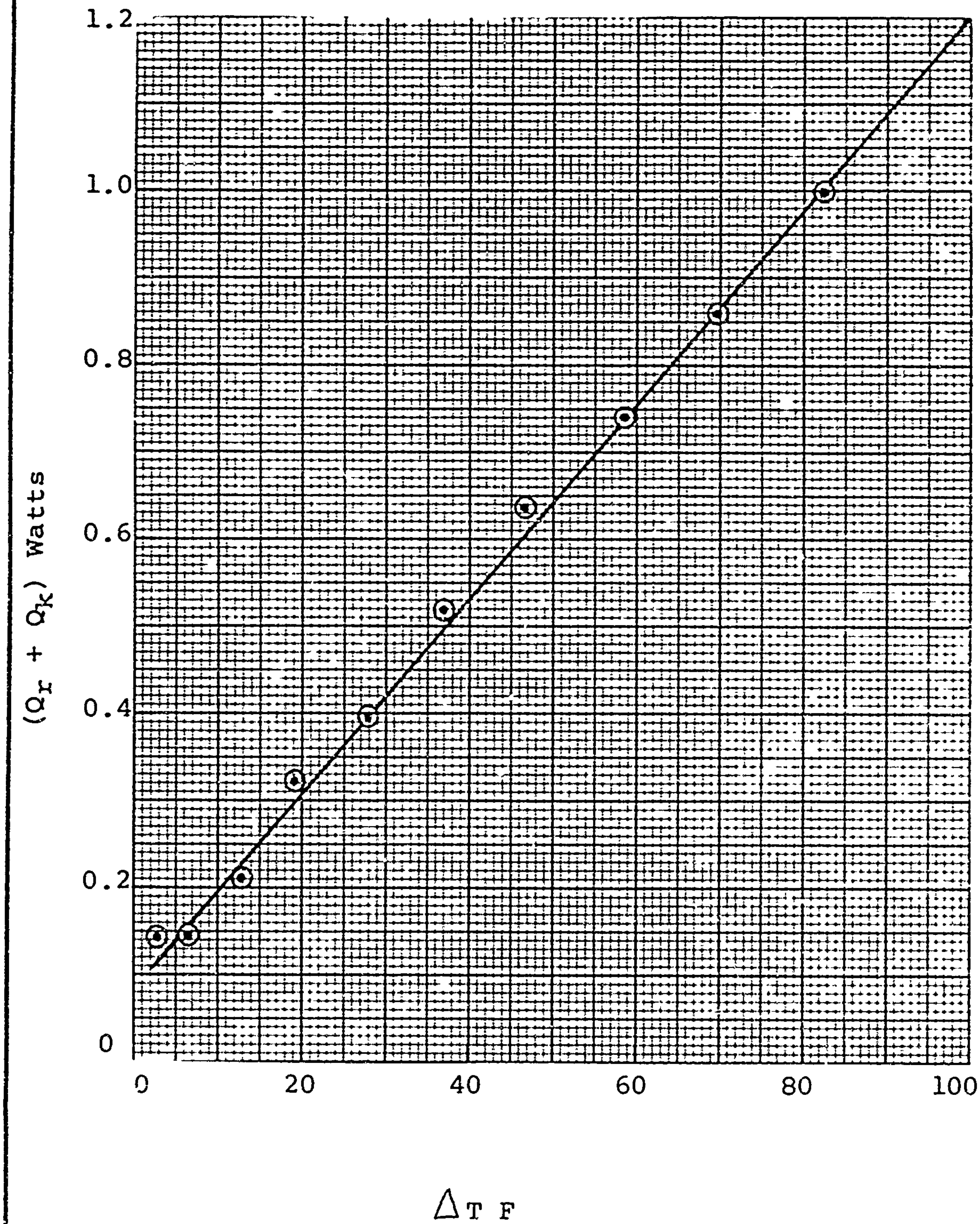


Figure 9
Variation of Radiation and Conduction Losses With Temperature Difference for the 0.25 Inch Diameter Test Cylinder

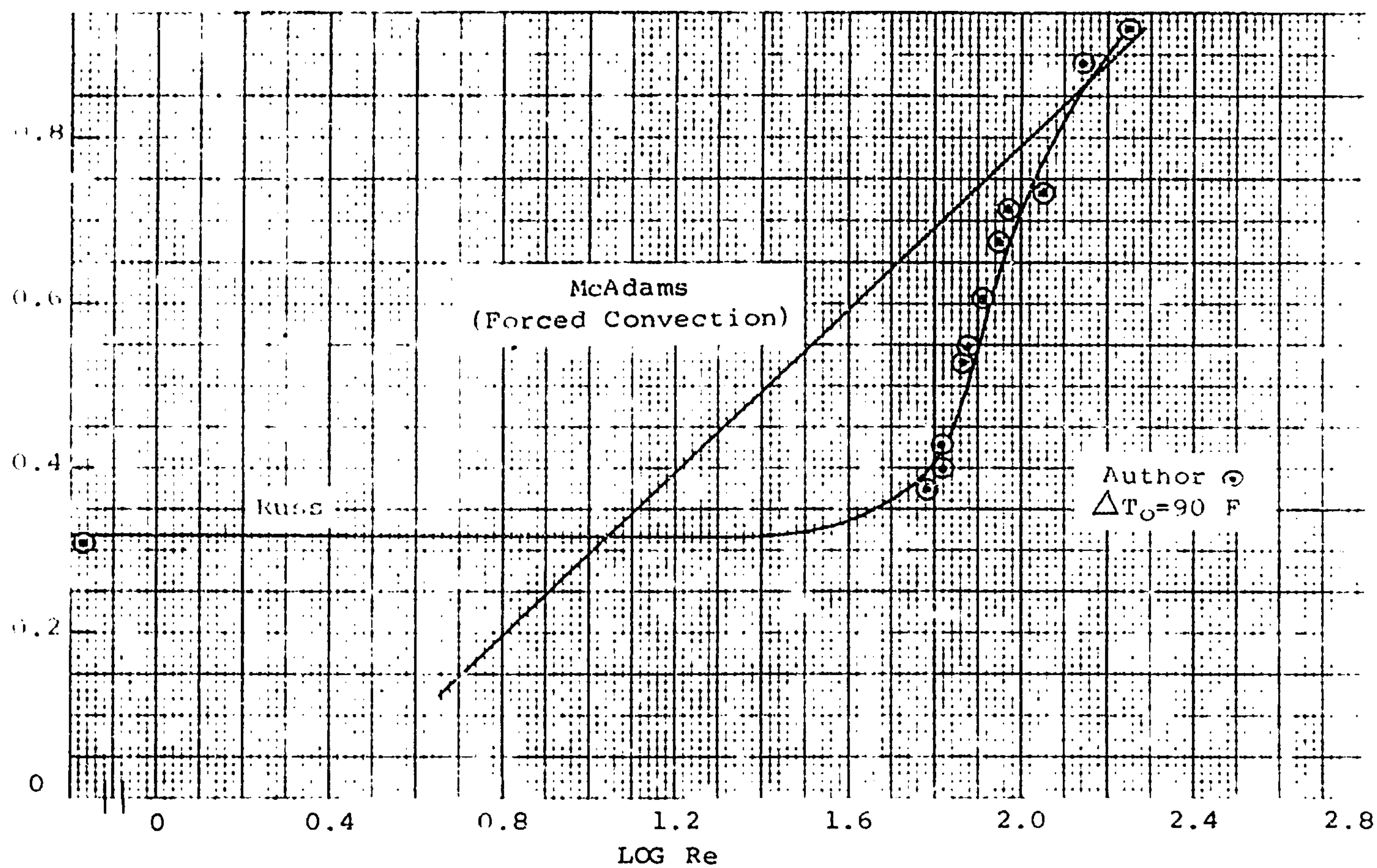


Figure 10
Variation of the Heat Transfer Coefficient With Vibration
Intensity At Low Intensities for the 0.08 Inch Diameter Test Cylinder

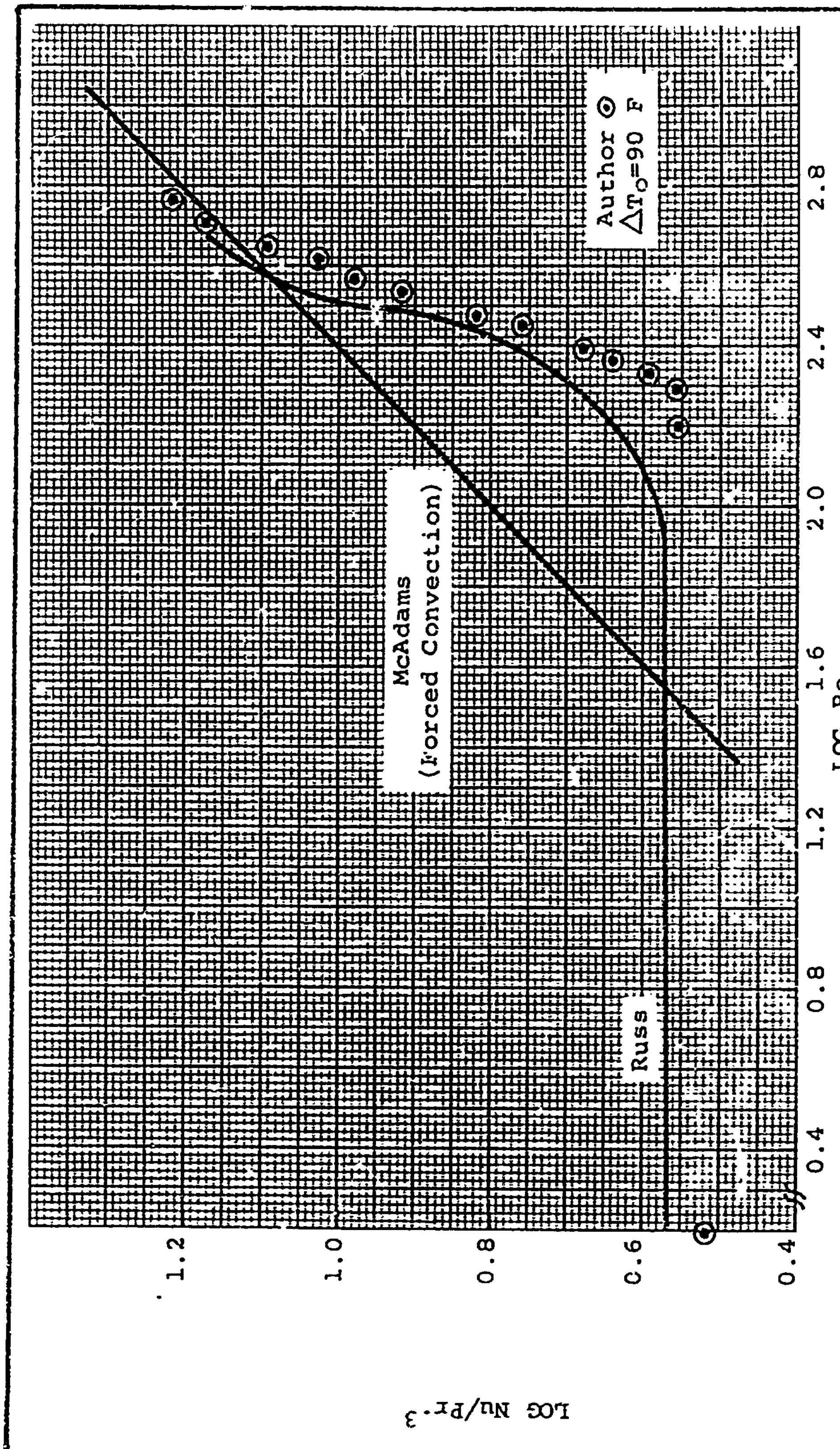


Figure 11
Variation of the Heat Transfer Coefficient With Vibration Intensity At Low Intensities for the 0.25 Inch Diameter Test Cylinder

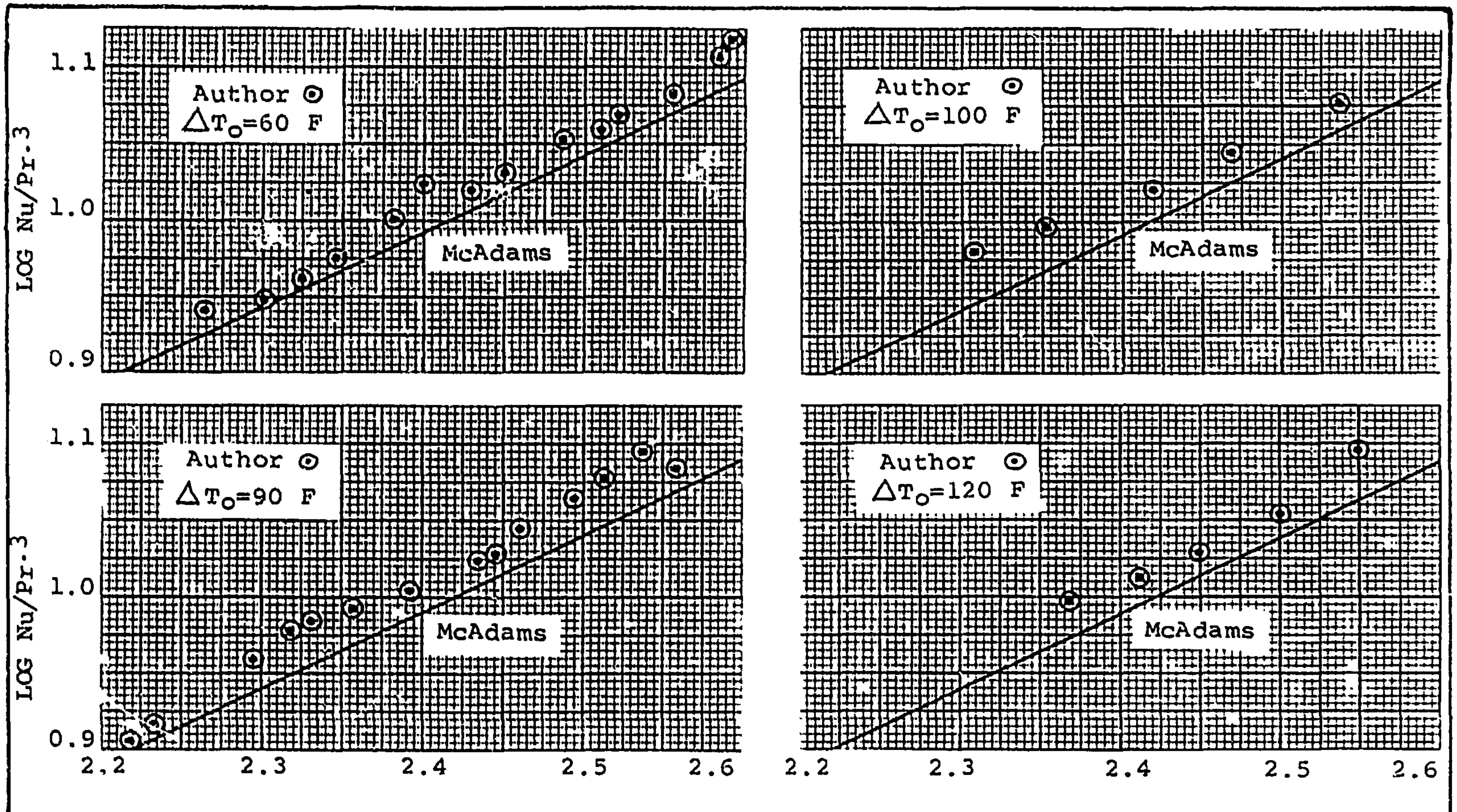


Figure 12
Variation of the Heat Transfer Coefficient With
Vibration Intensity At High Intensities for the 0.085 Inch Test Cylinder

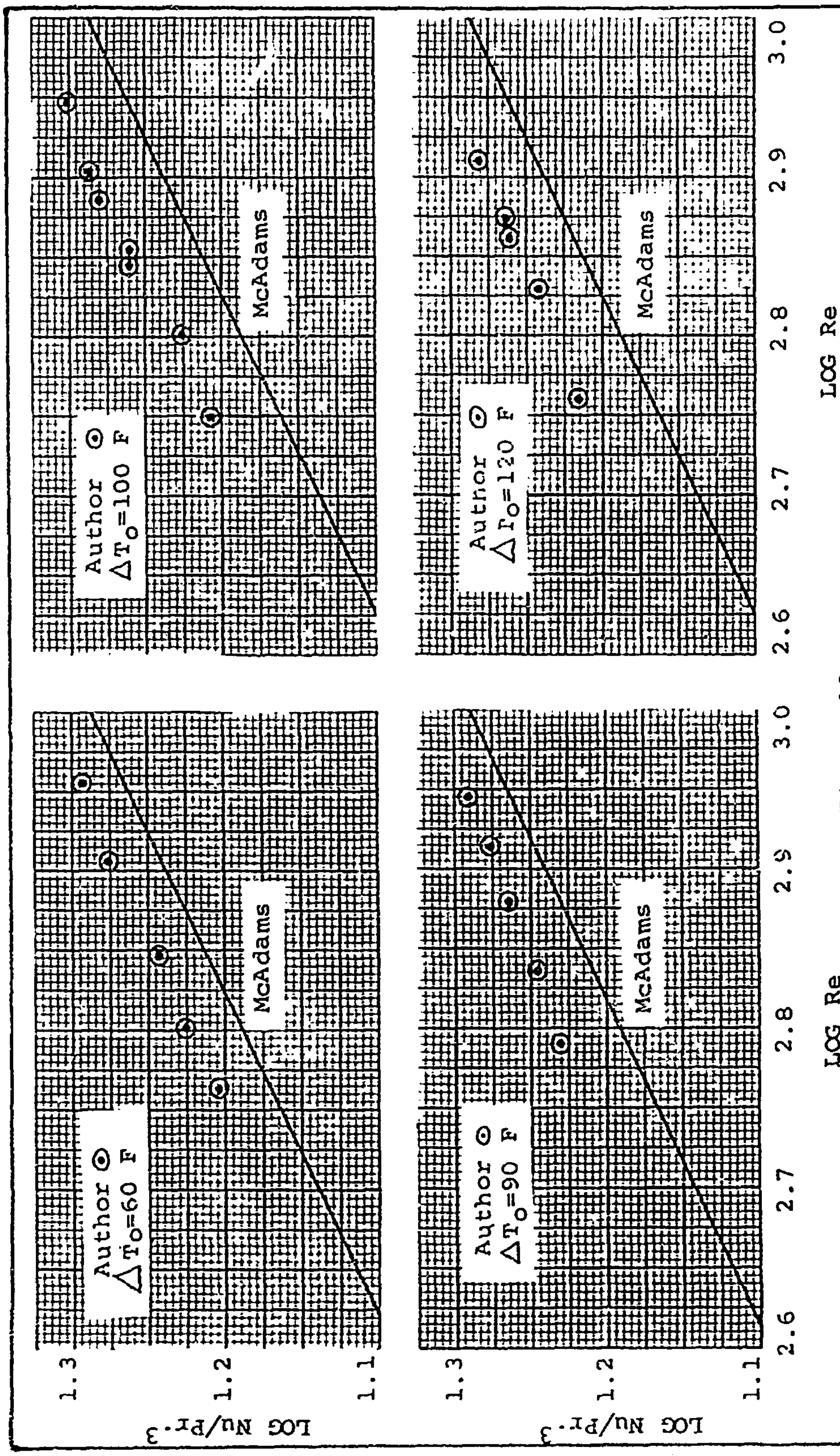


Figure 13

Variation of the Heat Transfer Coefficient With Vibration Intensity At High Intensities for the 0.25 Inch Test Cylinder

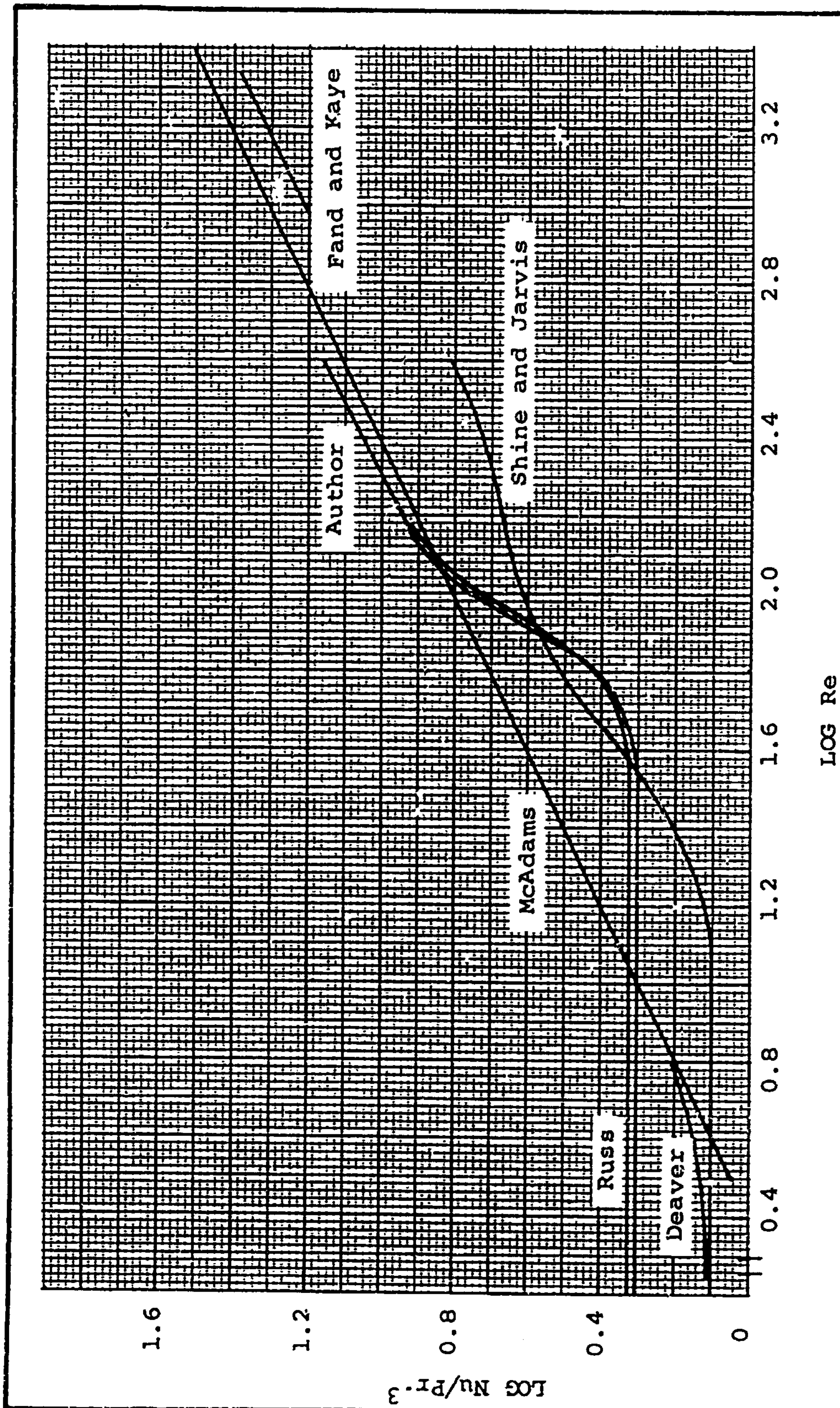
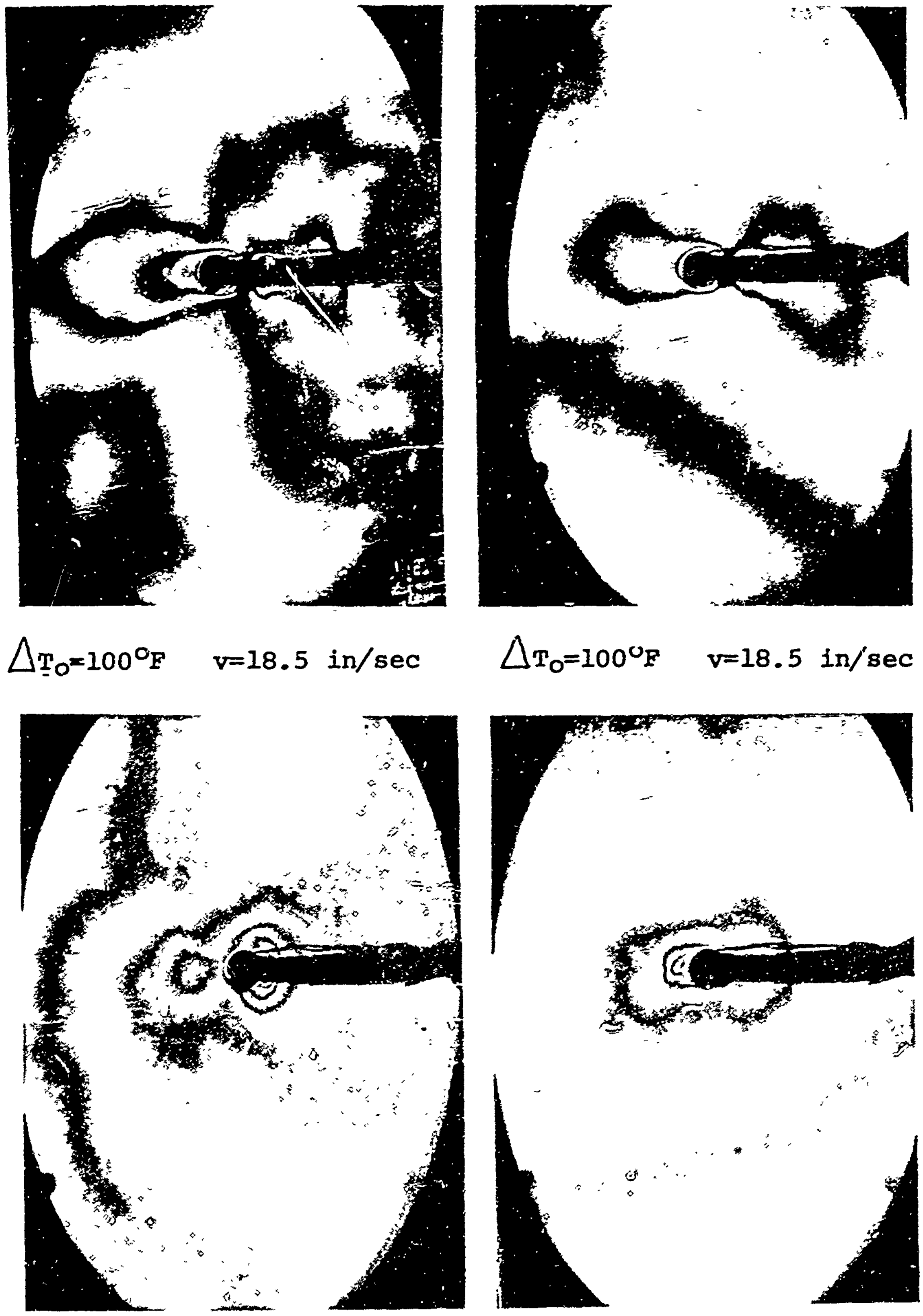


Figure 14
Correlation With Other Authors

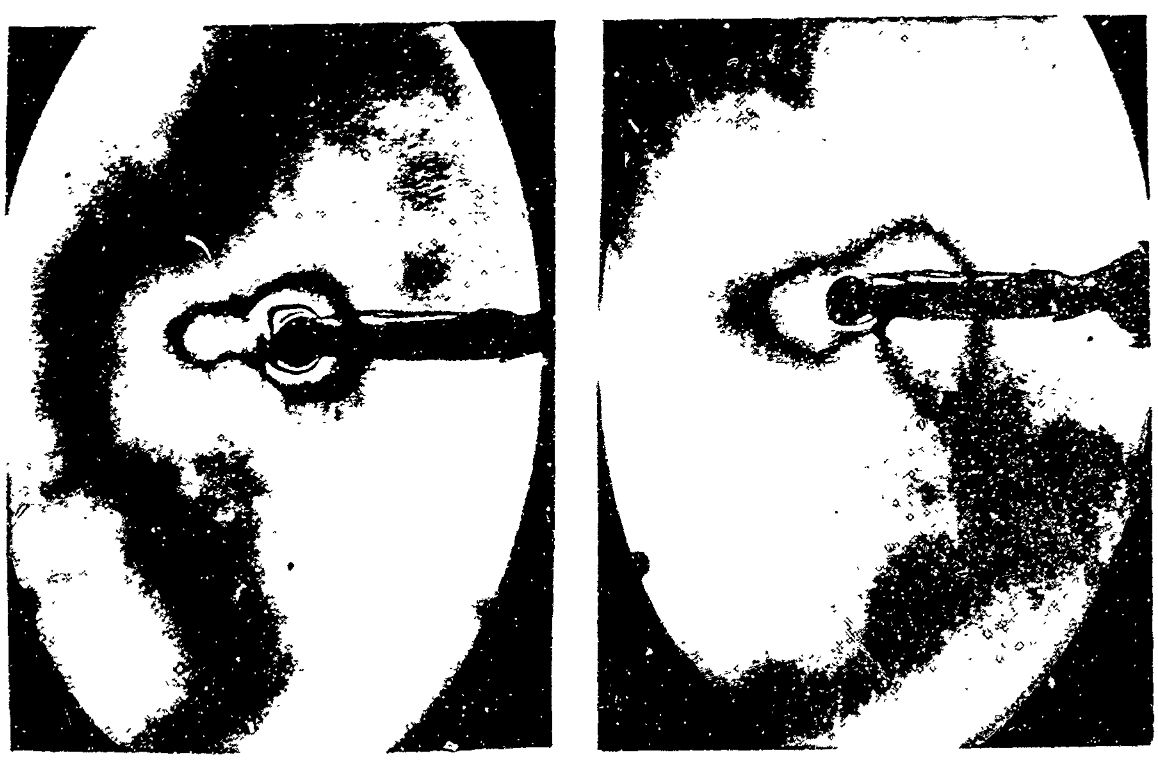


$\Delta T_o = 100°F$ v=18.5 in/sec $\Delta T_o = 100°F$ v=18.5 in/sec

$\Delta T_o = 120°F$ v=18.9 in/sec $\Delta T_o = 120°F$ v=18.9 in/sec

Figure 15
Interferograms of the 0.25 Inch Diameter Test Cylinder

ΔT_o=100°F v=19.8 in/sec ΔT_o=100°F v=19.8 in/sec



ΔT_o=120°F v=21.0 in/sec ΔT_o= 120°F v=21.0 in/sec

Figure 16
Interferograms of the 0.25 Inch Diameter Test Cylinder

APPENDIX B

Equation Development

Equation Development

The expression for the maximum error in convective heat transfer can be drived by writing the equation for this variable in finite difference form as

$$\Delta Q_c = \Delta Q_t - \Delta Q_1 - \Delta(Q_r + Q_k)$$

with

$$\Delta Q_t = I \Delta E + E \Delta I$$

$$\Delta Q_1 = 2IR \Delta I + I^2 \Delta R$$

$$\Delta (Q_r + Q_k) = \Delta Q_{t_o} - \Delta Q_{c_o} - \Delta Q_{1_o}$$

where the zero subscript indicates that the variable was measured during preliminary static runs to determine $(Q_r + Q_k)$, and the absence of the zero subscript indicates that the variable was measured during vibration tests. Since the cylinder was at rest during the preliminary static runs, there was no turbulence around the thermocouple. Consequently, the error in ΔT_o was assumed to be zero, and since ΔT_o was the only independent variable used in the determination of Q_{c_o}, it was assumed that ΔQ_{c_o} was also zero. Expanding the expressions for ΔQ_{t_o} and ΔQ_{1_o}, substituting, and combining terms results in

$$\Delta Q_c = I \Delta E + (E - 2IR) \Delta I + I^2 \Delta R$$
$$+ I_o \Delta E_o + (E_o - 2I_oR_o) \Delta I_o + I_o^2 \Delta R_o$$

APPENDIX C

Sample Calculation

Sample Calculation

This calculation was based on run #19 on the 0.25 inch diameter test cylinder. The recorded values of the measured variables were:

$T_w = 93.4$ F $I = 0.91$ amps $2a = 0.5439$ in

$T_a = 80.4$ F $E = 3.71$ volts $f = 82$ cps

From these data the following computations were made:

$$Q_t = IE = (0.91)\ (3.71) = 3.379 \text{ watts}$$

$$Q_1 = I^2R = (0.91)^2\ (0.167) = 0.138 \text{ watts}$$

$$\Delta T = T_w - T_a = 93.4 - 80.4 = 13 \text{ F}$$

$$T_f = \frac{(T_w + T_a)}{2} = \frac{(93.4 + 80.4)}{2} = 86.9 \text{ F}$$

Radiation and conduction losses were determined from Figure 10 as

$$(Q_r + Q_k) = 0.223 \text{ watts}$$

From tables in Eckert and Drake (Ref 2:509), the fluid properties were determined as

$$k_f = 0.01537 \text{ BTU/hr ft F}$$

$$\nu_f = 17.29\ (10)^{-5}\ \text{ft}^2/\text{sec}$$

$$Pr = 0.707$$

Convective heat transfer was obtained from

$$Q_c = Q_t - (Q_r + Q_k) - Q_1 = 3.018 \text{ watts}$$

The dimensionless parameters were calculated from

$$\frac{Nu}{Pr^{.3}} = \frac{1.184 Q_c}{k_f \Delta T \, Pr^{.3}} = \frac{1.184(3.018)}{0.01537(13)(0.707)^{.3}} = 19.85$$

and

$$Re = \frac{2af}{288\, \nu_f} = \frac{0.5439(82)}{288(17.29(10)^{-5}} = 896$$

Calculation of the maximum overall error in the Nusselt number and Reynolds number was calculated from

$$\Delta Nu = \frac{1.184\, \Delta Q_c}{k_f \Delta T} + \frac{1.184 Q_c \Delta(\Delta T)}{k_f\ (\Delta T)^2}$$

$$\Delta Re = \frac{(f \Delta 2a + 2a \Delta f)}{288\, \nu_f}$$

where

$$\Delta(\Delta T) = 0.5 \text{ F}$$

$$\Delta 2a = 0.01 \text{ in}$$

$$\Delta f = 2 \text{ cps}$$

The error in convective heat transfer was computed from

$$\Delta Q_c = I \Delta E + (E - 2IR) \Delta I + I^2 \Delta R + I_o \Delta E_o + (E_o - 2I_oR_o) \Delta I_c + I_o^2 \Delta R_o$$

with

$I = 0.91$ amps. $E = 3.71$ volts $R = 0.167$ ohms

$\Delta I = 0.015$ amps. $\quad \Delta E = 0.2$ volts $\quad \Delta R = 0$

$I_o = 0.4$ amps. $\quad E_o = 1.55$ volts $\quad R_o = 0.167$ ohms

$\Delta I_o = 0.015$ amps. $\quad \Delta E_o = 0.2$ volts $\quad \Delta R_o = 0$

or

$$\Delta Q_c = .91(.2) + \left[3.71 - 2(.91)(.167)\right].015 + (.4)(.2) + \left[1.55 - 2(.4)(.167)\right].015$$

$$= .182 + .0512 + .08 + .0213$$

$$= .334 \text{ watts}$$

Substituting,

$$\Delta Nu = \frac{1.184(.334)}{(0.1537)(13)} + \frac{1.184(3.018)(.5)}{(.01537)(169)} = 1.975 + .686$$

$$= 2.7$$

and

$$\Delta Re = \frac{82(.01) + .5439(2)}{288(17.29)(10)^{-5}} = \frac{1.907(10)^5}{288(17.29)} = 38$$

The value of the maximum error will be different for each run and the percent error will increase as the value of the parameter decreases.

APPENDIX D

Experimental Data

Table I
Static Data for Determining Radiation and Conduction Losses for 0.085 Inch Diameter Cylinder

Run	T_w °F	T_a °F	ΔT_o °F	GrPr	Nu	I_o amps	E_o volts	Q_{t_o} watts	Q_{c_o} watts	Q_{l_o} watts	$Q_r + Q_k$ watts
1	87.0	79	8.0	4.14	1.328	1.252	0.253	0.3166	0.1248	0.119	0.0728
2	92.5	79	13.5	6.78	1.426	1.560	0.310	0.4832	0.2264	0.186	0.0708
3	99.0	79	20.0	9.70	1.500	1.925	0.385	0.7412	0.3550	0.284	0.1022
4	105.0	79	26.0	12.21	1.556	2.222	0.450	0.9990	0.4820	0.379	0.1380
5	114.5	79	35.5	15.80	1.608	2.640	0.540	1.426	0.6840	0.538	0.2040
6	126.5	79	47.5	20.08	1.668	3.100	0.630	1.953	0.9580	0.746	0.2490
7	136.0	79	57.0	23.43	1.706	3.440	0.700	2.409	1.187	0.922	0.3000
8	156.0	79	77.0	29.91	1.762	4.075	0.840	3.422	1.680	1.302	0.4400
9	171.0	79	92.0	34.20	1.799	4.480	0.920	4.124	2.071	1.582	0.4710
10	186.0	79	107.0	37.92	1.820	4.900	1.020	5.000	2.462	1.902	0.636

Table II
Static Data for Determining Radiation and Conduction Losses for 0.25 Inch Diameter Cylinder

Run	T_w °F	T_a °F	ΔT_o °F	GrPr	Nu	I_o amps	E_o volts	Q_{t_o} watts	Q_{c_o} watts	Q_{l_o} watts	$Q_r + Q_k$ watts
1	89.0	86	3.0	37.72	1.825	0.24	0.93	0.223	0.071	0.009	0.143
2	93.0	86	7.0	86.01	1.825	0.30	1.17	0.351	0.188	0.015	0.148
3	99.0	86	13.0	154.3	2.253	0.40	1.55	0.619	0.383	0.027	0.209
4	105.0	86	19.0	218.1	2.388	0.50	1.92	0.959	0.597	0.042	0.320
5	114.0	86	28.0	306.2	2.530	0.60	2.32	1.392	0.939	0.060	0.393
6	123.0	86	37.0	394.4	2.638	0.70	2.72	1.902	1.301	0.081	0.520
7	132.0	85	47.0	491.0	2.749	0.80	3.10	2.480	1.733	0.107	0.640
8	144.0	85	59.0	597.2	2.842	0.90	3.50	3.150	2.275	0.135	0.740
9	155.0	85	70.0	684.3	2.919	1.00	3.81	3.810	2.790	0.167	0.853
10	168.0	85	83.0	781.0	2.991	1.10	4.25	4.675	3.423	0.202	1.050

Table III
Experimental Data for 0.25 Inch Diameter Test Cylinder

Run	T_w	T_a	ΔT	f	2a	I	E	Q_t	$Q_r + Q_k$	Q_1	Q_c	$Nu/Pr^{.3}$	Re
	°F	°F	°F	cps	in.	amps.	volts	watts	watts	watts	watts		
1	170.0	80.0	90.0	0	0	1.158	4.50	5.21	1.231	0.224	3.755	3.36	0
2	105.0	81.0	24.0	88	0.3579	1.158	4.50	5.21	0.349	0.224	4.637	16.35	618
3	108.0	81.0	27.0	88	0.3100	1.155	4.50	5.20	0.381	0.223	4.596	14.45	533
4	113.0	82.0	31.0	88	0.2773	1.150	4.50	5.17	0.427	0.221	4.522	12.30	472
5	118.0	82.0	36.0	88	0.2528	1.150	4.50	5.17	0.482	0.221	4.467	10.41	427
6	121.0	82.0	39.0	88	0.2251	1.150	4.50	5.17	0.519	0.221	4.430	9.50	378
7	126.0	82.0	44.0	88	0.2123	1.150	4.50	5.17	0.575	0.221	4.374	8.29	355
8	136.0	82.0	54.0	88	0.1903	1.150	4.50	5.17	0.690	0.221	4.259	6.53	312
9	143.0	82.0	61.0	88	0.1787	1.150	4.50	5.17	0.769	0.221	4.180	5.64	289
10	152.0	82.0	70.0	88	0.1620	1.150	4.50	5.17	0.870	0.221	4.079	4.774	259
11	158.0	82.0	76.0	88	0.1521	1.150	4.50	5.17	0.938	0.221	4.011	4.290	241
12	164.0	82.0	82.0	88	0.1397	1.150	4.50	5.17	1.050	0.221	3.899	3.850	219
13	169.0	82.0	87.0	88	0.1296	1.150	4.50	5.17	1.055	0.221	3.894	3.619	202
14	170.0	82.0	88.0	88	0.1036	1.150	4.50	5.17	1.075	0.221	3.874	3.555	161
15	96.2	80.4	15.8	82	0.3526	0.91	3.71	3.38	0.252	0.138	2.989	16.4	578
16	95.0	80.4	14.6	82	0.4277	0.91	3.71	3.38	0.241	0.138	3.000	17.6	703
17	93.8	80.4	13.4	82	0.4949	0.91	3.71	3.38	0.226	0.138	3.015	19.25	814
18	95.6	80.4	15.2	82	0.3842	0.91	3.71	3.38	0.250	0.138	2.991	16.82	632
19	93.4	80.4	13.0	82	0.5439	0.91	3.71	3.38	0.223	0.138	3.018	19.85	896
20	105.5	79.6	25.9	82	0.3817	1.20	4.91	5.88	0.370	0.241	5.269	17.30	616
21	104.0	79.6	24.4	82	0.4679	1.20	4.91	5.88	0.353	0.241	5.286	18.42	759
22	102.5	79.6	22.9	82	0.5423	1.20	4.91	5.88	0.335	0.241	5.304	19.71	882
23	104.9	79.6	25.3	82	0.4279	1.20	4.91	5.88	0.362	0.241	5.277	17.75	693
24	103.2	79.6	23.6	82	0.5080	1.20	4.91	5.88	0.344	0.241	5.295	19.09	825

Table III (cont.)
Experimental Data for 0.25 Inch Diameter Test Cylinder

Run	T_w	T_a	ΔT	f	2a	I	E	Q_t	$Q_r + Q_k$	Q_1	Q_c	$Nu/Pr^{.3}$	Re
	°F	°F	°F	cps	in.	amps.	volts	watts	watts	watts	watts		
25	109.6	83.1	26.5	81	0.4456	1.26	5.10	6.43	0.375	0.265	5.790	18.42	703
26	111.2	83.1	28.1	81	0.4054	1.26	5.10	6.43	0.391	0.265	5.774	17.30	637
27	112.8	83.1	29.7	61	0.3609	1.26	5.10	6.43	0.411	0.265	5.754	16.31	564
28	108.1	83.1	25.0	81	0.5076	1.26	5.10	6.43	0.360	0.265	5.805	19.65	803
29	107.5	83.1	24.4	81	0.5626	1.26	5.10	6.43	0.353	0.265	5.812	20.20	890
30	114.4	82.2	32.3	81	0.4797	1.38	5.65	7.80	0.442	0.318	7.040	18.40	749
31	117.5	82.2	35.3	81	0.3767	1.38	5.65	7.80	0.476	0.318	7.006	16.65	577
32	114.9	81.6	33.3	81	0.4324	1.38	5.65	7.80	0.453	0.318	7.029	17.75	676
33	112.8	80.5	32.3	81	0.4654	1.38	5.65	7.80	0.443	0.318	7.039	18.35	734
34	111.6	80.6	31.0	80	0.5241	1.38	5.65	7.80	0.428	0.318	7.054	19.21	816
35	108.1	81.6	26.5	80	0.4625	1.26	5.10	6.43	0.375	0.265	5.790	18.42	723
36	107.0	81.5	25.5	80	0.4919	1.26	5.10	6.43	0.365	0.265	5.800	19.25	771

Table IV
Experimental Data for 0.085 Inch Diameter Test Cylinder

Run	T_w	T_a	ΔT	f	2a	I	E	Q_t	$Q_r + Q_k$	Q_1	Q_c	$Nu/Pr^{.3}$	Re
	F	F	F	cps	in.	amps	volts	watts	watts	watts	watts		
1	166.0	76.0	90.0	0	0	4.48	0.92	4.12	0.512	1.581	2.027	2.011	0
2	100.0	76.0	24.0	88	0.3284	4.48	0.89	3.99	0.125	1.581	2.284	8.95	197
3	114.0	76.0	38.0	88	0.1957	4.48	0.90	4.04	0.208	1.581	2.251	5.51	114
4	159.0	82.0	77.0	88	0.1146	4.48	0.90	4.04	0.435	1.581	2.024	2.35	62
5	121.0	82.0	39.0	88	0.1656	4.48	0.90	4.04	0.214	1.581	2.245	5.30	95
6	109.0	82.0	27.0	88	0.2353	4.48	0.90	4.04	0.142	1.581	2.317	7.98	137
7	105.0	82.0	23.0	88	0.3077	4.48	0.90	4.04	0.119	1.581	2.340	9.50	181
8	104.0	82.0	22.0	88	0.3614	4.48	0.90	4.04	0.113	1.581	2.346	9.96	213
9	139.0	82.0	57.0	88	0.1347	4.48	0.90	4.04	0.318	1.581	2.141	3.41	75
10	148.0	82.0	66.0	88	0.1226	4.48	0.90	4.04	0.371	1.581	2.088	2.86	67
11	131.0	82.0	49.0	88	0.1476	4.48	0.90	4.04	0.273	1.581	2.186	4.08	83
12	155.0	82.0	73.0	88	0.1194	4.48	0.90	4.04	0.412	1.581	2.047	2.52	65
13	137.0	82.0	55.0	88	0.1369	4.48	0.90	4.04	0.307	1.581	2.152	3.57	76
14	124.0	82.0	42.0	88	0.1550	4.48	0.90	4.04	0.232	1.581	2.227	4.87	88
15	168.0	84.0	84.0	88	0.0684	4.48	0.91	4.09	0.475	1.581	2.034	2.15	36
16	85.5	75.0	10.5	81	0.6859	3.45	0.70	2.41	0.052	0.927	1.434	12.99	389
17	86.5	75.3	11.2	81	0.6386	3.45	0.70	2.41	0.056	0.927	1.430	12.13	362
18	87.1	75.3	11.8	81	0.5763	3.45	0.70	2.41	0.058	0.927	1.428	11.50	325
19	87.9	75.5	12.4	81	0.5028	3.45	0.70	2.41	0.063	0.927	1.423	10.89	284
20	89.0	75.6	13.4	81	0.4308	3.45	0.70	2.41	0.068	0.927	1.418	10.02	242
21	88.9	78.8	10.1	81	0.7043	3.45	0.70	2.41	0.050	0.927	1.436	13.45	393
22	90.3	78.8	11.5	81	0.5942	3.45	0.70	2.41	0.057	0.927	1.429	11.75	332
23	90.7	78.8	11.9	81	0.5471	3.45	0.70	2.41	0.059	0.927	1.427	11.35	305

Table IV (cont.)
Experimental Data for 0.085 Inch Diameter Test Cylinder

Run	T_w	T_a	ΔT	f	2a	I	E	Q_t	$Q_r + Q_k$	Q_l	Q_c	$Nu/Pr^{.3}$	Re
	°F	°F	°F	cps	in.	amps	volts	watts	watts	watts	watts		
24	91.5	78.9	12.6	81	0.4519	3.45	0.70	2.41	0.063	0.927	1.423	10.66	251
25	91.8	78.9	12.9	81	0.4919	3.45	0.70	2.41	0.065	0.927	1.421	10.41	274
26	93.9	80.0	13.9	81	0.4031	3.45	0.70	2.41	0.070	0.927	1.416	9.58	223
27	94.6	80.0	14.6	81	0.3811	3.45	0.70	2.41	0.073	0.927	1.413	9.12	211
28	95.0	80.0	15.0	81	0.3602	3.45	0.70	2.41	0.075	0.927	1.411	8.85	199
29	95.3	80.1	15.2	81	0.3339	3.45	0.70	2.41	0.077	0.927	1.409	8.70	184
30	106.0	87.0	19.0	78	0.6133	4.48	0.91	4.08	0.095	1.581	2.404	11.76	316
31	108.5	88.0	20.5	77	0.5490	4.48	0.91	4.08	0.104	1.581	2.395	10.81	278
32	110.5	88.0	22.5	77	0.4536	4.48	0.91	4.08	0.116	1.581	2.383	9.82	229
33	111.0	88.0	23.0	77	0.4120	4.48	0.91	4.08	0.120	1.581	2.379	9.55	207
34	115.0	88.0	27.0	77	0.3051	4.48	0.91	4.08	0.142	1.581	2.357	8.04	158
35	119.0	88.0	31.0	77	0.2539	4.48	0.91	4.08	0.166	1.581	2.333	6.91	126
36	101.7	83.0	18.7	77	0.6327	4.48	0.91	4.08	0.092	1.581	2.407	12.01	327
37	102.0	83.0	19.0	77	0.6136	4.48	0.91	4.08	0.095	1.581	2.404	11.81	316
38	103.0	83.0	20.0	77	0.5777	4.48	0.91	4.08	0.102	1.581	2.397	11.18	297
39	104.0	83.0	21.0	77	0.5322	4.48	0.91	4.08	0.108	1.581	2.391	10.61	274
40	105.0	83.0	22.0	77	0.4820	4.48	0.91	4.08	0.113	1.581	2.386	10.11	248
41	106.0	83.0	23.0	77	0.4206	4.48	0.91	4.08	0.119	1.581	2.380	9.64	215
42	107.0	83.0	24.0	77	0.3832	4.48	0.91	4.08	0.125	1.581	2.374	9.20	196
43	110.0	83.0	27.0	77	0.3179	4.48	0.91	4.08	0.142	1.581	2.357	8.10	162
44	101.0	83.0	18.0	77	0.6597	4.48	0.91	4.08	0.089	1.581	2.410	12.50	341
45	98.9	80.5	18.4	77	0.6958	4.48	0.91	4.08	0.091	1.581	2.408	12.30	362
46	104.6	81.6	23.0	80	0.4929	4.63	0.95	4.40	0.120	1.695	2.585	10.49	263

Table IV (cont.)
Experimental Data for 0.085 Inch Diameter Test Cylinder

	T_w °F	T_a °F	ΔT °F	f cps	2a in.	I amps	E volts	Q_t watts	$Q_r + Q_k$ watts	Q_1 watts	Q_c watts	$Nu/Pr^{.3}$	Re
47	106.7	81.6	25.1	80	0.3841	4.63	0.95	4.40	0.131	1.695	2.574	9.55	205
48	105.8	81.6	24.2	80	0.4229	4.63	0.95	4.40	0.126	1.695	2.579	9.93	226
49	103.4	81.6	21.8	80	0.5526	4.63	0.95	4.40	0.109	1.695	2.596	11.12	296
50	101.8	81.6	20.2	80	0.6471	4.63	0.95	4.40	0.103	1.695	2.602	12.05	348
51	105.2	77.1	28.1	80	0.4831	5.10	1.04	5.31	0.150	2.065	3.095	10.30	261
52	106.2	77.1	29.1	80	0.4339	5.10	1.04	5.31	0.155	2.065	3.090	9.94	234
53	104.1	77.1	27.0	80	0.5249	5.10	1.04	5.31	0.141	2.065	3.104	10.79	283
54	100.2	77.1	23.1	80	0.6610	5.10	1.04	5.31	0.120	2.065	3.125	12.70	358
55	102.4	77.2	25.2	80	0.5823	5.10	1.04	5.31	0.131	2.065	3.114	11.60	315

Vita

Captain David F. Neely was born [redacted] He attended grade school and high school there and was appointed to the United States Naval Academy in July, 1947. He graduated from the Naval Academy in 1951, and was commissioned as a second lieutenant in the United States Air Force. At that time he entered pilot training. Upon completion of pilot training, he was assigned to duty with the Tactical Air Command at Shaw Air Force Base, South Carolina. Subsequently, he entered resident training for Astronautical Engineering (Graduate) at Wright-Patterson Air Force Base, Ohio.

Permanent address: [redacted]

This thesis was typed by Mrs. Edna M. Kluesner.